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BY

JAMES PARK,

DEAN OF THE FACULTY AND PROFESSOR OF MINING IN THE UNIVERSITY OF OTAGO;
CORRESPONDING MEMBER OF COUNCIL OF THE INSTITUTION OF MINING AND METALLURGY;
FELLOW OF THE GEOLOGICAL SOCIETY OF LONDON;
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PREFACE TO SECOND EDITION.

In preparing this edition for the press all the chapters have been revised ; and some have been recast or entirely rewritten with the object of weaving into them matter relating to the more recent advances in geologic science. The sections devoted to the growth and origin of coral reefs and atolls, with the author's own observations in the South Pacific; to mountain-building; the morphology of coastal topography, and the rôle of pneumatolysis in the formation of ore-deposits, have been greatly extended.

Parts I. and II. cover the courses prescribed in Physical and Stratigraphical Geology for the B.A. and B.Sc. degrees; while Part I. meets the requirements in Physical Geology as defined for the B.E. degree in Civil and Mining Engineering.

In the preparation of this edition I wish to acknowledge my special indebtedness to Professor Otto Wilckens, Ph.D., for his revision of the chapter on Historical Geology, the section on the Alpine Trias, and the fossil names ; also for many valuable suggestions as to prehistoric man, and the Ice Age in Europe. The thoroughness of the research work carried out by Professor Wilckens is known to all geologists.

During the work of revision, much help and advice was given by my colleagues in New Zealand, and to all of them I make grateful acknowledgment.

JAMES PARK.

Otago University
Dunedin, N.Z.

EXTRACT FROM

PREFACE TO FIRST EDITION.

THIS volume comprises a systematic course of lectures carefully revised and expanded so as to cover the requirements in Geology as now defined for Engineering, Mining, and Agricultural Schools and Colleges.

The first principles of Geology are, so to speak, the ABC of the science. They are mostly based on the simple processes that are now going on around us. But the student who confines his observations and studies to his own immediate neighbourhood is in danger of acquiring a false sense of proportion, and may in time unconsciously come to believe that the things and processes he sees in his own terrain are typical of the whole globe. When he afterwards comes to travel further afield he may find himself compelled to modify his standards and renounce many of his early conceptions. The corrective of local prejudices and a narrow horizon is extensive reading and still more extensive travel.

I desire to acknowledge my indebtedness to the Director of the Geological Survey of the United States for permission to utilise the illustrations of the Survey's publications, a privilege of which I have fully availed myself; to Dr Tempest Anderson for the use of Plate XVI. and Figure 123; to Mr E. F. Pittman, Government Geologist for New South Wales, for the use of Plate XXXVIIIA.; and to my Publishers, who have courteously placed at my disposal many of the figures scattered throughout the text, as well as the beautiful plates of fossils illustrating Chapters XXII. to XXXIII.

JAMES PARK.

UNIVERSITY OF OTAGO, DUNEDIN, N.Z.,
January 1914.

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PART I.

PHYSICAL GEOLOGY.

CHAPTER I.

SOME FIRST PRINCIPLES.

BEFORE proceeding with the detailed study of the crust of the Earth and the processes that have modified its surface, it is necessary as a first step to take a bird's-eye view of the whole history of the globe from its beginning up to the present time. By pursuing this course we shall acquire a better understanding of the facts subsequently presented; for it is obvious that when the ground-plan of the structure, so to speak, has been reviewed and intelligently grasped, the filling in of the details will be a matter of comparative ease.

The Earth when viewed in its widest sense is found to consist of three concentric envelopes, namely (1) the *Atmosphere*;[1] (2) the *Hydrosphere*;[2] and (3) the *Lithosphere*.[3]

The *Atmosphere* is the outer gaseous envelope, the *Hydrosphere* the watery envelope, and the *Lithosphere* the solid rocky crust on which we live.

The central core enclosed by the Lithosphere is called the *Barysphere*[4] from its supposed greater density.

The *water-surface* of the globe comprises about 145 million square miles, and the *land-surface* about 52 million square miles.

GENERAL OUTLINE OF GEOLOGICAL HISTORY.

Scope and Purpose of Geology.—Geology deals with the character, origin, and arrangement of the rocks forming the crust or outer shell of the globe. It also concerns itself with the mode of occurrence and identification of the remains of the plants and animals that are found embedded in certain rocks. By the systematic study of these fossil remains and of the conditions that govern the formation of sediments in our existing seas, supplemented by a shrewd knowledge of the habits of the animals and plants that now people and clothe the Earth, the geologist has been able, without resort to random shots, to unravel the long succession of epoch-making happenings that have

[1] Gr. *atmos*=vapour, and *sphaira*=a sphere.
[2] Gr. *hydor*=water, and *sphaira*.
[3] Gr. *lithos*=a stone, and *sphaira*.
[4] Gr. *barys*=heavy, and *sphaira*.

given the crust its present form, to define the relative ages of the different groups of strata, to construct a panorama of the stream of life that has passed across the stage of bygone time, and to present a view of the climatic conditions and environment in which this varied life flourished and died.

Geology deals with the riddle of the Earth, and is pre-eminently the science of the open field and mountain slope, the river-valley and rocky strand.

The geologist applies the present to read the past, and in doing so he is surely on safe ground, for the present is merely a continuance of the past. He recognises that the same air and the same precipitation of watery vapour in the form of rain have existed since the beginning of geological time, that water in the form of running streams has always played a dominant *rôle* in wearing away the solid land, and that seas and lakes as occupying the hollows and depressions have always, as now, been the places where the rocky detritus carried down by the streams has been sorted and spread out.

The Origin of the Earth.—The Earth is a planet belonging to our solar system. From the researches of the astronomer we learn that many of the so-called fixed stars are suns, each moving in its own orbit, and each, like our own Sun, attended by a system of dark satellites or planets.

An investigation of the heavenly bodies has shown that some exist in the form of intensely heated incandescent gases, some as globular masses of highly heated glowing liquid matter, and others, like our own Earth, as dark solid bodies. According to the *nebular hypothesis*, it is supposed that the solid bodies were at one time masses of incandescent gases, and that they became first liquid and then solid through the radiation of their heat into space.

When the heated globular body had become sufficiently cool, a solid crust, at first thin and brittle, formed on the surface. As the loss of heat continued, the glassy crust became thicker and thicker, and in its endeavours to adapt itself to the shrinking dimensions of the molten interior mass, became seamed with cracks and wrinkled into ridges and valleys, like the skin of a dried-up apple.

It is almost certain that through the cracks and fissures floods of uprising molten matter spread over the thin crust, portions of which collapsed and became engulfed, leaving pools and lakes of liquid magma over which a new crust gradually formed.

In course of time the scarred and gnarled igneous crust became cool enough to permit the condensation of the watery vapours that enveloped the Earth. A portion of the waters settled in the hollows and formed the first seas and lakes that ever existed on the face of the globe; while another portion penetrated the dry land, thereby forming the springs from which the first streams and rivers took their source.

The restless waters of the new-born seas at once began to wear away the dry land along their shores, and the streams draining the valleys to deepen and widen their channels. The denuded material was spread out in layers and beds on the rocky floor of the seas, thus marking the beginning of the conditions of sedimentation that have prevailed without interruption up to the present day.

It was not till the precipitation of the dense aqueous vapours had taken place and the waters were gathered together into seas that life appeared on the globe.

Beginning of Geological Time.—Geological time dates back to the beginning of the physical conditions that now prevail upon the Earth; that is, to the time when detrital matter derived from the denudation of the dry land first began to be spread out in the form of beds or layers on the floor of the

juvenile seas and lakes. These ancient sediments formed the first records of geological time.

The Action of Water in Destroying and Re-forming.—From that date up till now, water has continued to be the most powerful agency in sculpturing and modifying the surface of the Earth. In wasting and eroding the dry land, in transporting the eroded material, in sorting and spreading it out, the action of water has been unceasing throughout all time up to the present day.

The amount of matter forming the Earth is practically a fixed quantity; hence it is obvious that all the deposits and beds now exposed in the dry land must have been derived from the destruction of the first igneous crust, or of sedimentary rocks of later date.

Ever since the beginning of geological time the dry land has been denuded by water, yielding the material to form new deposits in seas and lakes. Through the progressive crumpling of the crust these deposits in course of time became raised above sea-level, forming dry land which, in its turn, was subjected to the agents or erosion, thus yielding material to form newer deposits or strata. This action is still going on, the older formations providing the material for the younger.

From this it will be seen that the same material has appeared re-sorted in different forms, in different geological ages. It is now easy to understand how some of the older formations have been entirely removed by this everlasting denudation, or are represented only by isolated remnants of small extent.

This cycle of denudation, with deposition of sediments and submergence, followed by uplift, renewed denudation, and deposition, has been going on ever since the beginning of geological time.

No portion of the original igneous crust, or even of the first-formed sediments, has ever been found; but shreds and patches may still exist, buried beneath the deposits of later times.

The Ocean Basins not Permanent.—The existing dry land of the globe is found to be mainly composed of aqueous or sedimentary rocks, from which it is known that the present distribution of land and water is not that which always existed. On the contrary, by slow movements of the crust extending over countless ages, known to geologists as *secular movements*, and by mountain-building movements, and by subsidence along fault-lines, some portions of the crust have been elevated, while others have been depressed or submerged. In this way the seas and dry land have been changing places, so to speak, all through geological time; the effect of this wandering of the seas has been to cover the whole of the first igneous crust of the Earth with sedimentary rocks.

The sedimentary formations were deposited on the floor of the sea, marginal to the land that provided the detritus of which they are composed. Strata containing freshwater shells and fishes, and sometimes beds of rock-salt, tell us of the former existence of continents, inland lakes, and mediterranean seas of which no vestige now remains.

Genetic Classification of Rocks.—The rocks forming the stony crust of the Earth fall into three great classes:—

I. **Terrestrial Deposits,** including river, lake, and glacial drifts, loess and desert-sands.

II. **Thinogenic,**[1] that is, composed of sediments laid down as shore-deposits. Typical of this class we have conglomerates, sandstones, shales, marls, and clays.

III. **Biogenic,**[2] that is, composed of the stony remains of living organisms.

[1] Gr. *this-thinos*=shore deposits, and *genesis*=production.

[2] Gr. *bios*=life and *genesis*=production.

In this class we have shelly and coral limestones; chalk, mainly composed of minute protozoans called Foraminifera; limestones composed of calcareous algæ; cherts composed of Radiolaria; and deposits of diatomaceous earth.

IV. **Pyrogenic**,[1] that is, of igneous origin as granite, syenite, diorite, basalt, and rhyolite. All lavas and dyke rocks belong to this class, as well as the fragmentary material ejected by volcanoes.

Terrestrial Deposits may be conveniently divided into those formed by rivers, ice, and wind. Of these, by far the most important are river drifts, that in some regions form wide-spreading fans, piedmont coastal plains, steppes, tundras, pampas or savannas, covering hundreds of square miles of territory. They also fill in lake-basins and reclaim vast areas from the sea.

As a sheet of variable thickness, Pleistocene glacial drifts cover a large part of Northern Russia, Prussia, and North America.

Anemogenic[2] or wind-formed deposits, as loess and desert-sands, are among the most important of the superficial coverings of the rocky crust. Loess is typically developed in the larger continents, in the cold temperate zones, where there was a great extension of ice in the Glacial period. In China it covers whole provinces, and is widely spread in Northern Russia and North America. Desert-sands are the product of arid conditions, and hence more abundant in highland, tropical, and sub-tropical regions than in the higher latitudes.

Wind-borne sands are a feature of sea-coasts in all latitudes, except perhaps the Arctic and Antarctic. In the tropical coral islands of the Pacific Ocean, where the sea swarms with Foraminifera, coral sands and silts mingled with the remains of Foraminifera are sometimes spread by the wind over the coastal lands for a distance of half-mile or more, forming false-bedded calcareous deposits. The limestones of the Junagarh type[3] on the sea-board of Arabia and on the Deccan may possibly be æolian rather than marine; that is, formed by minute marine organisms carried inland by the wind.

Thinogenic rocks are the most important of all the rock-types. They are composed of sediments laid down on the floor of the sea between high-water mark and the edge of the continental shelf. On the landward side they pass into terrestrial deposits, and at the edge of the continental shelf merge into the abyssal deposits. Genetically considered, they consist of the products of land erosion, intercalated with accumulations of calcareous organisms that become limestones. Enclosed in rocks of thinogenic origin are the organic remains that have made it possible to construct the geological column and unravel the succession of life on the globe. Quantitatively considered, three-quarters of the rocks forming the stony crust are composed of marine sediments.

Biogenic Deposits owe their existence to the activities of certain organisms, for the most inhabitants of the sea. In consequence of subsidence, or other geographical changes, the remains of these organisms become interbedded with the mechanically formed sediments derived from the waste of the dry land.

Pyrogenic rocks appear at the surface as dykes and bosses uncovered by denudation, or as overflow volcanic matter. A genetic relationship exists between volcanic activity and mountain-building. In regions of intense folding, or faulting, the molten magma is squeezed into fissures, and in places

[1] Gr. *pyr*=fire, and *genesis*=production.
[2] Gr. *Anemos*=the wind, and *genesis*=production.
[3] J. W. Evans, "Mechanically-formed Limestones from Junagarh and other Localities," *Quart. Jour. Geol. Soc.*, vol. 56, pp. 559–583; 588–589.

appears at the surface as lava flows. That is, igneous intrusion is an expression of intense crustal movements.

The Earth's Crust mostly Sedimentary.—An examination of the fabric of the outer shell of the Earth shows that it is principally composed of stratified rocks; that is, rocks occurring in parallel beds or layers. A study of the materials forming these rocks, and of their fossil contents, shows us that they have been formed by the gradual deposit of sediments on the floor of some sea or lake, or in some cases by precipitation from solutions, or in others by the growth and accumulation of animal or vegetable organisms.

The physical structure of sedimentary or aqueous rocks—as they are sometimes called—is dependent on three main factors, namely:

(1) The *texture* of the material.
(2) The character of the *cementing medium*.
(3) The amount of *induration*, *alteration*, or *metamorphism* to which the material has been subjected.

The term *texture* refers to the coarseness or fineness of the constituent grains or pebbles.

Streams and rivulets, as well as the ebbing and flowing tide of the sea, have through all the ages possessed the same eroding, transporting, and sorting power, and what we now see going on in our valleys and along our shores is a fair example of what took place in earliest geological time.

The denudation or wearing away of the dry land was mainly the work of running water, while the sorting and spreading out of the denuded material was effected by the laving action of the waves of the sea as they advanced and retreated on their ancient strands.

The gravels were piled along the shore in the shallow water; the smaller pebbles were carried into deeper water; while the sands and finer particles were borne further seaward, the latter forming beds of mud at the extreme limit of the deposit.

The gravels along the sea littoral, when consolidated, formed *conglomerates*; the water-borne sands, *sandstones*; the more distant muds, *mudstones* and *shales*; while the shell-banks and coral reefs became *limestones*.

Folding and Tilting of Sedimentaries.—The older sedimentary strata have been of necessity subject to all the later movements that have affected the crust of the Earth. They have been indurated by the great weight of superincumbent strata and other processes, and plicated or corrugated by entanglement in great crustal folds. Hence the strata do not always occupy the horizontal position in which they were originally laid down, but are inclined or tilted at various angles, being arranged in folds with gentle or steep slopes.

Alteration of Sedimentaries.—Many of the older rocks have been altered or metamorphosed by the rearrangement of their constituent minerals. Thus limestones have been changed to marbles, sandstones to quartzite, mudstones and shales to slates and schists.

The agencies principally concerned in the metamorphism of sedimentary rocks have been pressure, which induces the schistose and slaty structures; heat and circulating waters, which cause a rearrangement of the constituents, whereby a crystalline structure may be formed. Hence *metamorphic* rocks are often spoken of as *crystalline*. Many crystalline rocks split readily into thin laminæ and form what are called *schists*.

Origin of Igneous Rocks.—Throughout all geological time the outer crust or shell of the Earth has been subject to the intrusion and overflow of molten *magmas* from below.

Whether the interior is in (*a*) a molten state, or (*b*) exists in a highly heated, but enormously compressed, condition ready to assume the liquid form whenever and wherever the stress is relieved, or (*c*) whether the lavas that are from time to time erupted come from huge subterranean caverns of molten rock that have escaped the general cooling of the crust, is at present not known to geologists.

Rôle of Igneous Intrusions.—Though subordinate in extent and mass, igneous rocks have played an important part in the occurrence and distribution of ore-bodies and mineral deposits. Not only are they metalliferous themselves, but in many cases their intrusion has fissured and shattered the rocks they penetrated, thus permitting the invasion of the fissured country by the metal-laden gases and vapours that emanated from the intruding magma.

Thus we find that the igneous intrusion frequently played a double *rôle* in the formation of ores:

(*a*) By fracturing and fissuring the rocks.
(*b*) By supplying the metalliferous gases and waters which deposited their mineral contents in the fissures.

Intrusive igneous rocks have also played an important part in folding, crumpling, and tilting the sedimentary strata which they have broken through, or with which they have come in contact. Moreover, in many parts of the globe volcanic flows and fragmentary ejecta have been piled up so as to form mountain-chains or isolated mountains that frequently attain a great height.

Alteration of Igneous Rocks.—All igneous rocks, like sedimentaries, are subject to alteration. Superheated steam has frequently caused a rearrangement of the constituents; while the circulation of thermal waters has led to the removal of some constituents and the replacement of others. Such alteration products are called *secondary* minerals. It is also found that intense pressure may cause altered lavas and tuffs to assume a schistose structure not unlike that induced in metamorphosed sedimentary rocks.

Interior of the Earth.—Of the interior condition of the globe almost nothing is known, except that the density is greater, and that the temperature increases with the depth, although not at a uniform rate in different places.

The mean density or specific gravity of the whole globe has been determined to be about 5·5, and that of the materials forming the outer portion of the crust to which man has access, about 3. The inference to be drawn from this is that the interior or Barysphere must be composed of materials possessing a greater mean density than those forming the outer shell or Lithosphere.

It has been contended by some writers that the interior must possess a nucleus of iron, or of iron alloyed with nickel and other heavy metals.

The Planetesimal Hypothesis.—This view of the origin of the Earth as elaborated by Chamberlin and others is a modification of the Nebular Hypothesis. It assumes that the great incandescent nebula[1] which originally composed the solar system cooled relatively rapidly, the cooled gases taking the form of myriads of solid meteorites to which the name *planetesimals*[2] has been applied. Under the influence of gravity the solid meteorites segregated into spiral clusters that eventually became the nuclei of the sun, the planets and their satellites. During this aggregation, the meteorites are believed to have bombarded one another with great violence, thereby becoming hot.

The main source of the high temperature of the sun and of the earth before it cooled was not due to the heat generated by the collision of the constituent

[1] Lat. *Nebula*=a cloud, fog, or mist.
[2] Meaning infinitely small planets.

meteorites, but to the contraction and consolidation of the mass after the meteorites had come into contact.

All solid bodies possess a potential energy proportional to their distance from, or height above, the common centre of gravity of the globular mass to which they belong. Thus a block of stone resting on the edge of a high tower possesses a large store of this *energy of situation*, which it loses as soon as it falls to the ground. The energy is not lost, but merely transformed into heat.

The packing or crowding of a swarm of meteorites under the influence of gravity, which always acts towards the centre of the mass, is acompanied by the generation of great heat. Meteoric matter is a good conductor of heat, and hence the whole mass would soon assume a uniform temperature. As the packing continued, the globular mass would, in time, reach its maximum density, and thereafter gradually became cool by the radiation of heat from its surface.

The *heat of contraction* might not inconceivably be sufficient to melt the materials in the upper layers, but the lower layers would remain solid as the pressure of the superincumbent mass would be sufficient to prevent expansion, without which liquefaction cannot take place.

The more fusible materials in the upper layers, in accordance with the *law of liquation*, would rise to the surface, and in process of time solidify as a stony crust. The tendency of this process of differentiation would be to divide the constituent materials of the Earth into three distinct zones corresponding to the heavy metal, lighter sulphide regulus, and still lighter stony slag formed in a reverberatory furnace.

The central core and regulus form the barysphere; while the stony slag or crust, now modified and re-sorted by the action of subaerial agencies, constitutes the lithosphere or stony envelope.

The Planetesimal hypothesis has not received the general support of physicists and astronomers.

DIASTROPHISM OR CRUSTAL DEFORMATION.

Joints, fault-dislocations, and rock-folding are merely the physical expressions of crustal stresses. Formerly rock-deformation was attributed to the shrinking of the molten nucleus whereby the outer shell, being left unsupported, gradually became wrinkled. Dana was the first to doubt the adequacy of this cause to produce all the effects observed. He noted that the great folded zones occur near, and parallel with, the deeper ocean-basins. Observation has shown that the folded zones are composed of vast piles of comparatively deep-water sediments of fairly uniform lithological character; while in the undisturbed areas the same formations are represented by a less thickness of shallow-water sediments that may be intercalated with freshwater and terrestrial deposits. It is obvious that immense piles of uniform sediments can only be laid down on a sinking sea-floor where the rate of subsidence and deposition permit the depth of water to remain constant. Dana postulated that zones of folding began as long narrow depressions of the crust, to which he gave the name *geosynclinals*.

Of the various explanations that have been put forward, to account for the downward movement along the trough of the geosynclinals and the uplift of other segments, is *isostasy*. According to this view a planetary body rotating on its axis, under the influence of gravity, tends to assume a form in which the crustal stresses are in a state of equilibrium. Denudation of the continents and the piling up of the detritus on the ocean-floor, by a simple redistribution of the external load, tend to disturb the former condition of static equilibrium.

By the overloading of the ocean-floor sinking takes place in the zone of deposition; and this is accompanied by the *creep* of the continent towards the ocean basin. The creep may continue till the geosynclinal becomes overthrust; and in any case it will be progressive till isostatic equilibrium has been once more established. In this way we get the fulfilment of the postulate that,—mountain-chains arise on the sites of geosynclinals.

In other words, when the overloading disturbed the isostatic equilibrium, diastrophic movement began. Such diastrophic movements were major events in the Earth's history that profoundly influenced the development of life.[1] Many ancestral forms date back to the diastrophic periods, which were times of geographic and climatic change.

It is certain that, in the main, the diastrophic periods were distinguished by the magmatic intrusions that originated the whole series of after-eruption processes by which many valuable ore-deposits were formed.

Succession of Life in Geological Time.—Examination has shown that the earlier strata contain a few indistinct and badly preserved remains of plants and animals of a very primitive type.

Beds or formations higher in the succession are found to contain a larger and more varied assemblage of plant and animal life, many of a highly complex structure, including molluscs, fishes, huge bird-like lizards, saurians, palms, and tree-ferns.

The higher, *i.e.* younger, deposits contain, besides molluscs and fishes, the remains of many mammals which have representatives living at the present time. In other words, there has been a gradual succession of life throughout geological time from the lowly to the more highly organised forms, this succession of life being characterised by a singular persistency of the primitive types.

The Origin of Life.—The problem of the origin of life is still unsolved. We do not know when life first appeared on the Earth nor what form it took. If we are right in our conception of the Earth as a cooling satellite of the Sun, we are probably not far from the truth in believing that when life first appeared the conditions and environment were such as to render its perpetuation difficult and precarious. Perhaps the first ray of life glowed feebly for a time, flickered, died, and became rekindled many scores of times before it eventually succeeded in establishing itself in the saline waters gathered in the hollows of the still steaming crust.

The first assemblage of life of which we have any knowledge appeared in the Cambrian epoch. It comprised representatives of most of the great groups of marine invertebrates, and burst on the geological horizon with the suddenness of a meteor in a September sky. From what we now know of biological processes, it is obvious that this highly specialised congeries of life was preceded by a pre-Cambrian ancestry, of which no certain trace has yet been found.

It is probable that the primordial germs of life were tiny nuclei of jelly-like colloidal matter possessing no higher volition than the "Brownian dance" of motes in a beam of sunlight. As time rolled on, the stream of life gradually increased in volume by the continual accession of more and more complex forms, eventually culminating in the advent of man. We can easily conceive that this stately procession of life could only come into existence as the result of increasing food supply, increasing sunshine, wider seas, and more settled climatic conditions.

The distinctive organic types that constitute the great natural orders of animal life appear suddenly at different epochs and are still represented by

[1] Rollin T. Chamberlin, "Diastrophism and the Formative Processes," *Jour. of Geology*, vol. xxii., No. 4, May–June 1914, p. 316.

living forms. The sudden appearance of a new type possessing highly specialised structural features that place it on a higher plane than its kin, the persistence of this new type and the equally sudden advent at a later period of another type as superior to the last as the last is to the first, tend to show that life has progressed by a series of ascending, but sharply defined, steps or stages.

The processes of continuous variation, or mutation, that enabled a certain individual of a well-established type to develop functions that removed it and its progeny to a higher plane, while its kindred continued without change through succeeding eons, is one of the unsolved problems of biological science. The processes of evolution are still as obscure as they were to the speculative mind of Empedocles, "the father of the evolution idea" in the fifth century B.C., or to the more philosophical Aristotle, in the fourth century B.C., who with wonderful insight postulated that "Nature was a unified development, giving things forming a continuous line of descent from inanimate matter." After a long hiatus the work of Buffon and Erasmus Darwin, in the eighteenth century, paved the way for the researches of Lamarck, Darwin, and Wallace, which placed the vague ideas of the causes of variation on a philosophical basis. The theory of a common ancestry also gained strength from the remarkable similarities that were shown by Darwin and others to take place in the embryological developments of different creatures.

Palæontology teaches us that many genera appeared suddenly, flourished for a time and then disappeared. But the Orders and Families to which these extinct forms belonged have been carried on by related genera that would seem to have possessed greater powers of adaptation to a changing environment. Each new type from the date of its appearance has persisted up till now. Hence as we ascend the geological scale the more highly organised forms overspread the less highly developed. Hence if we draw a vertical ordinate through the orders of life that exist in late Cainozoic time, it will be found to represent a complete column of all the known types of life that have appeared on the geological stage from the beginning of time.

The primitive, intermediate, and higher types are still coeval.

The highly organised forms are more sensitive to climatic and other changes than the hardier Radiolarians and other lowly types. Hence, if the Earth becomes decadent and the conditions of life less and less favourable, the first types to disappear will be those that were the last to come into existence; and the last to survive will be the simple primordial forms. In other words, life will disappear in the inverse order of its appearance.

Geological Time marked by Distinctive Life.—Close investigation has shown that certain organic forms occur only in certain beds or strata. Such fossils are termed characteristic or distinctive forms. Geologists have taken advantage of these to divide geological time into periods, just as historic time is divided into periods by succeeding dynasties or empires. These periods are purely empirical, and are merely used for convenience of description and study.

Tetrahedral Hypothesis.—If we examine a terrestrial globe we cannot fail to observe that the great mass of the dry land lies in the Northern Hemisphere, and the greatest expanse of sea in the Southern Hemisphere. Moreover, we shall at once see that the continental units and seas are frequently triangular in shape, the former presenting their bases to the north and tapering to the south.

Further, we shall find that the continents and seas are approximately antipodal or opposite to one another.

The unequal distribution of land in the two Hemispheres, the dominant triangular shape of the geographical units, and the antipodal distribution of

the land and seas cannot be set down to mere coincidence or fortuitous happening, but to the operation of well-defined physical laws.

As so clearly demonstrated by Lothian Green, the arrangement of the continental units approximates the shape of the tetrahedron,[1] which is a figure bounded by four triangular planes. The great oceans lie on the flattened or depressed triangular faces of the figure.

Now a sphere is the figure which presents the smallest surface for its volume, and the tetrahedron the greatest.

So long as a globular mass possesses heat it will continue to shrink, and the inner portion, on account of its greater heat, will contract more rapidly than the outer rigid shell. As the cooling and internal shrinking proceed, the globular mass will, in time, be encumbered with an excess of surface which will be most easily disposed of by assuming the form of the tetrahedron.

When a metal tube collapses under compressive stress, as may be easily demonstrated in a compression-testing machine, it becomes triquetral—that is, bounded by three concave sides. As viewed in cross-section, each of the three projecting lobes is seen to be opposite a depression.

The antipodal arrangement of the land and seas is the natural corollary of the tetrahedral form assumed by a rotating globular mass.

The Age of the Earth.—Almost from the beginning attempts have been made to define the age of the Earth in terms of our solar chronology. Even primitive man recognised that the Earth had a beginning and will surely have an end. He believed that the present condition of the Earth is merely transitional and not final. The folk-lore of all peoples—Chaldean and Greek, Maori and Red Indian—contains many quaint legends as to the birth of Mother Earth. But the endeavour to determine the duration of geological time did not originate till last century. In 1859, from the rate of chalk erosion in Kent, Darwin estimated that the excavation of the Wealden Valleys had required a period of 300 million years. This extravagant estimate Darwin afterwards abandoned.

In 1860, on the basis of the thickness of the geological column of sediments, and the rate of accumulation, John Phillips estimated that the geological record covered a period of between 38 and 96 million years.

In 1862, Professor W. Thomson, afterwards Lord Kelvin, attacked the problem on a physical basis, and in the succeeding thirty-five years made many estimates of the age of the Earth. He drew attention to the fact that the Sun could not continue to radiate heat for an unlimited time. From the Earth's present store of heat, as deduced from underground temperature gradients, he calculated that the consolidation of the crust took place about 100 million years ago. The rate of dissipation of the stored thermal energy of the Earth formed the main basis of all his estimates. In 1865, Thomson showed the importance of the tides in terrestrial dynamics. The final result of the tides is to act as though a gigantic friction-brake were being slowly applied. He concluded that a time would arrive when the relative motion between the Earth and Moon should be no more.

In 1875, Professor Tait thought that the utmost limit that could be allowed from the physical side, since vegetable life of the lowest form appeared, could not exceed 10 million years.

In 1876, Thomson narrowed his limits to 50 and 90 million years, and in later years reduced these limits still further.

Sir George Darwin, basing his estimate on the supposed genetic relationship between the Earth and the Moon, assigned a minor limit of 56 million years since their separation.

[1] Gr. *Tetra*=four, and *hedra*=a base or plane.

In 1893, Clarence King, assuming the temperature of initial crustal solidification to be 2000° C., and taking into consideration the effect of pressure in raising the melting-point of rocks and the necessity of an earth that should be stable under the influence of tidal stresses, estimated that the period of cooling which would reduce the gradient to that of the present was limited by 24 million years.

In 1897, in his last estimate, Lord Kelvin narrowed his earlier estimates to 20 and 40 million years.

In 1899, Sir Archibald Geikie,[1] basing his estimate on the rate of accumulation of river-silts, concludes that the whole of geological column may have taken about 100 million years to accumulate. On the same basis, de Lapparent supposes the age to be 75 or 80 millions.[2]

In 1900, Professor Sollas, assuming the mean rate of accumulation to represent the maximum, obtains 26 million years.[3]

The estimates of the age of the Pleistocene glaciation based on the climatic changes that were supposed by James Croll (1868) to accompany the precession of the equinoxes are now regarded as of little intrinsic value.

In 1909, Professor J. Joly suggested the sodium content of the sea as an age-index of the oceans. The sodium content is approximately determinable, but the annual rate of increment is unknown; hence the difficulties that are presented by this method are as formidable as those encountered in the geological and physical methods. Assuming that the increment has remained practically constant throughout geological time, Joly[4] estimates the age of the oceans to be 90 million years.

According to the hypothesis of Laplace, the stored thermal energy of the Earth was that originally derived from the solar nebula, and it was on the basis of the gradual dissipation of this initial heat that the early estimates of Kelvin and others were computed. It is now recognised that the surface temperature of the Earth can owe but little to its internal heat. The genial surface warmth is almost wholly due to the absorption of solar radiant heat. And for this reason the duration of life on our planet is intimately bound up with that of the Sun. On the other hand, the energy of the Sun may be mainly due to radio-thermal action which is regenerative or self-stimulative.

The discovery of radium and the thermal energy of radio-activity suggests that the Earth may be in thermal equilibrium, gaining as much as it loses. If this view be established, the basis of the estimates of Kelvin and other physicists is destroyed. The cooling can only proceed as the slow decay of the radio-elements permits. Hence it is impossible to determine the age of the Earth from its thermal condition.

In 1905, Professor Boltwood suggested the use of radio-active minerals as an age-index. Since then much experimental work on the stored-up energy of radio-active minerals and their rate of decay has been carried out by Rutherford, Shoddy, Strutt, Joly, Boltwood, and Holmes. Estimates of the age of the Earth by Joly and others based on the decay of the helium, uranium, and thorium groups of radio-active elements range from 1000 to 1500 million years. These figures are bewildering, and must be accepted with caution, as after all there may be some flaw in the physical argument.

Climatic Changes.—Changes of climate are known to have taken place in the geological past. It is now recognised that periods of glaciation have

[1] *Brit. Assoc. Rept.*, address to Section C, 1899.
[2] *Traité de Géologie*, vol. iii. p. 1860.
[3] *Brit. Assoc. Rept.*, address to Section C, 1900.
[4] *Radio-activity and Geology*, 1909, p. 247.

alternated with periods of genial conditions. Many explanations have been advanced to account for these climatic changes, some based on cosmic, others on terrestrial, conditions. Some of these hypothesis have been accepted and eventually discarded.

Prominently among the supposed causes are changes (*a*) in the aqueous envelope; (*b*) in the solar activity; (*c*) in the carbon dioxide content of the atmosphere affecting the storage of solar radiation; in the astronomical relationship of the Earth and Sun; in the distribution of land and water; in the position of the Earth's axis; in the attitude of the land relatively to sea-level.

The causes that have received the most support are based on cosmic causes. In 1832, Adhémar, a celebrated French mathematician, drew attention to the changes of eccentricity of the Earth's orbit round the Sun, and the fact that during the summer season of the Southern Hemisphere the Earth is in its nearest position to the Sun (perihelion), while during the winter season of the same hemisphere the Earth is at its greatest distance from the Sun. He argued that as the shape of the orbit was variable, during the periods of greater eccentricity of the orbit, the hemisphere whose winter falls in aphelion would undergo a protracted period of winter cold. In this way stupendous masses of ice would accumulate near the pole in aphelion, and as a further consequence the centre of gravity of the Earth might be shifted. He computed that the periods of extensive glaciation would recur alternately in each hemisphere at intervals of 10,500 years.

James Croll [1] (1873) elaborated Adhémar's hypothesis by showing the dependence of the prevailing winds and ocean currents upon the eccentricity of the Earth's orbit.

Astronomers generally have objected to Adhémar and Croll's views. They maintain that the variation of eccentricity could have but a slight effect on the Earth's climate. They also reject the view which postulates that the climatic changes arose from the wandering of the Earth's axis of rotation.

Dupont, who made a special study of the evidences of climatic changes in the geological past, maintains that there have been no changes of climate, and that all the known variations could be accounted for by changes in the distribution of land and water. This explanation is now favoured by many geologists, though it is recognised that science has not yet solved the climatic problem of the Ice Age.

The climate of the Palæozoic epoch is generally believed to have been uniform throughout the year. There were no seasonal changes and no zones of varying temperature, apart from those arising from alpine elevation. Botanical provinces were absent; and the universal character of the Carboniferous coal vegetation implies a nearly absolute equality in the distribution of heat and light over the whole globe (de Lapparent).[2]

According to White the majority of the trees of the Devonian and Carboniferous forests in the Temperate zone reveal no evidence of seasonal change. The secondary wood of the *Calamite* does not show any regular zones of growth comparable with the annual rings of existing forest trees.[3] This also is true of the *Lepidodendra*.[4]

With the advent of the Permo-Carboniferous and Permian there came about

[1] *Climate and Time*, London, 1873.

[2] A. de Lapparent, *Traité de Géologie*, 5th ed., Paris, 1906, p. 989; and David White, "The Palæozoic Floras," *Am. Jour. Geol.*, vol. xvii., 1909, p. 336.

[3] A. C. Seward, *Fossil Plants*, vol. i., 1898, p. 313.

[4] *Ibid.*, vol. ii. p. 93; and D. White, *Am. Jour. Geol.*, vol. xvii., 1909, p. 338.

a decided change in the growth of the forest vegetation. The faintly indistinct rings of the Carboniferous trees now give place to well-marked and regular rings that indicate an annual seasonal growth of wood fibre, as well exhibited in the *Dadoxylon* from the Permo-Carboniferous of New South Wales, Queensland, and Brazil.[1]

In the pine of the Lias (*Araucaria*) the wood has become homogeneous and fibrous, and the concentric rings and medullary rays are well-defined, narrow, and regular, as the *Araucarioxylon* from the Upper Lias of Whitby.[2]

GEOLOGICAL HISTORY OF EARTH SUMMARISED.

We may summarise the successive stages through which the Earth has passed up to the beginning of the conditions that now prevail as follows :—

(1) In the beginning the Earth was a mass of nebular incandescent gases swinging through space.

(2) Through loss of heat by radiation the gases eventually became condensed into a highly heated viscous globular body.

(3) By continued loss of heat a solid crust formed on the surface of the liquid globe.

(4) In process of time the crust became thicker and thicker, and in its attempts to adapt itself to the smaller dimensions of the rapidly contracting heated interior, became crumpled and wrinkled like the skin of a dried apple.

(5) When the cooling had sufficiently advanced, the aqueous vapours that enveloped the Earth became condensed, and the waters settled on the land, forming streams and rivers which denuded or wore away the rocky crust.

(6) The streams flowed into the hollows or depressions in which were formed the first seas and lakes that ever existed.

(7) The muds, sands, and gravels carried down by the streams were sorted and spread out on the floor and along the strand of the seas, forming aqueous or sedimentary deposits that were thus the first records of geological time.

(8) It was probably soon after streams and seas came into existence that life first appeared on the globe.

(9) Since the beginning of geological time the dry land has been subject to denudation by the action of moving water. The formation of aqueous deposits has, therefore, been continuous throughout all geological time in those portions of the globe occupied by seas and lakes; but as the areas of denudation and deposition have been constantly changing places, deposition has never been continuous in any one area.

(10) Through the slow secular crumpling of the Earth's crust causing elevation in one portion and subsidence in another, the older formations in course of time became dry land, and thus provided the material to form newer and younger formations.

(11) In the continuous cycle of erosion, deposition, and uplift that has always prevailed, the same material has appeared re-sorted in different forms.

(12) Since the beginning of geological time the sedimentary strata which comprise the great bulk of the known crust have been intruded

[1] David White, *Am. Jour. Geol.*, 1907, p. 622.

[2] A. C. Seward, *The Jurassic Flora*, 1900, p. 68.

by igneous dykes, or broken through and covered in places with streams of lava and volcanic ash.

(13) The strata originally laid down in a horizontal position have been folded by slow secular crustal movements, and frequently broken, crushed, and tilted at various angles by igneous intrusions.

(14) *Sedimentary* and *igneous* rocks alike are subject to alteration or metamorphism, forming the class of rocks called *metamorphic*.

(15) The fossil remains enclosed in the rocks show a gradual evolution from the lowly to the more highly organised types now inhabiting the globe, but the primitive forms have been persistent through all time.

(16) The *Nebular Hypothesis* supposes that the Earth was a nebula of incandescent gases, the heat of which gradually radiated into space till in process of time the planet became a globular mass of glowing molten matter in which the heavier metallic constituents segregated themselves, under the influence of gravity, into a heavy central core, forming the barysphere; while the lighter material arranged itself as an outer concentric layer.

In course of time the glowing mass cooled sufficiently to allow the outer envelope to form a solid crust. And as the heated interior of the Earth contracted more rapidly than the outside crust, the surface of the crust became crumpled and wrinkled in its endeavours to accommodate itself to the rapidly diminishing dimensions of the interior.

When the outer envelope had sufficiently cooled, the aqueous vapours, which up till now covered the surface in a dense impenetrable cloud, became condensed and soon settled in the hollows. Thereafter, the agents of denudation began the cycle of destruction, sorting, and reconstruction, which has continued without intermission through all the geological ages.

(17) The *Planetesimal Hypothesis* assumes that the primeval gaseous nebula of our solar system cooled rapidly and resolved itself into a vast spiral cluster of solid meteorites called planetesimals, which, under the operation of gravity, became segregated into knots. The largest knot formed the nucleus of the Sun, the smaller knots the nuclei of the planets.

The packing and contraction of the meteorites is believed to have generated sufficient heat to permit the differentiation of the constituents into a central barysphere and an outer lithosphere.

Thereafter the crumpling, denudation, and reconstruction of the stony crust proceeded as postulated in the nebular hypothesis.

(18) The age of the Earth has been estimated at periods ranging from 20 to 1500 million years. The estimates based on the accumulation of the geological column of sediments, and on the sodium content of the oceans have been multiplied many times by those founded on the rate of decay of radio-active minerals.

(19) The climate of the Palæozoic is believed to have been uniform throughout the year, the character of the Carboniferous vegetation implies an equal distribution of heat over the whole globe. In the Permian the forest trees exhibit evidence of seasonal growth. In the Lias the annular rings of the pines are almost as clearly defined as in our existing forest trees.

CHAPTER II.

THE HISTORY OF GEOLOGY.

THE whole scope of geological investigation is contained in two principal divisions:

(a) General Geology.
(b) Mining or Economic Geology.

General Geology,[1] with which we are mainly concerned, covers a wide field of scientific research. It deals with the origin and structure of the rocky materials forming the crust of the Earth, with the manner in which the strata are arranged or disposed, and with the agencies that have brought about the present configuration of the surface. It also concerns itself with the chronological succession of the various groups of rocks, and attempts to classify the strata in accordance with their fossil contents.

Mining Geology, also called **Economic** or **Applied Geology,** is a highly specialised branch of geology that possesses a peculiar interest to the miner and mining engineer. It concerns itself with the mode of occurrence, origin, and classification of mineral deposits of all kinds, with water supply, and the occurrence and genesis of mineral oil and oil-shales. Its study is seldom attempted till a knowledge of the fundamental principles of General Geology have first been acquired.

As a true science geology dates from the close of the eighteenth century. Before that time there were, even among scientists, many theories relating to the origin of earthquakes, volcanoes, fossils, and other phenomena that to us, with our better knowledge, seem curious and sometimes whimsical.

Among the founders of the science as we now know it, the names of the contemporary workers, Abraham Gottlob Werner, Professor of Mining at Freiberg; James Hutton, M.D., of Edinburgh; and William Smith, an English land-surveyor, stand pre-eminent.

Smith was the first to show by actual field observation that stratified rocks could be identified and arranged in chronological sequence according to their fossil contents. By his epoch-making work on the Jurassic rocks of South-West England, he laid the foundation of Stratigraphical Geology. His famous "Geological Map of England and Wales," published in 1815, was the first attempt to represent the geological relationships of the different rock-formations over an extensive tract of country, and subsequently it became the model of all geological maps.

Werner, a persuasive and eloquent teacher, maintained that the organic remains found in different rock-formations bore a constant relation to the age of the deposits. He affirmed that all rocks above the basal granites, gneisses, and metamorphic rocks were of aqueous origin, including the trap rocks; and this contention formed the cardinal doctrine of the school known as Neptunists.

[1] Gr. *ge*=the earth, and *logos*=description, discussion.

Hutton recognised the aqueous origin of sandstones, shales, and limestones, and in his philosophical writings forcibly discussed the consolidation, uplift, tilting, and bending of strata. He considered crustal movements as due to *extreme heat and expansion* supplemented by volcanic disturbance and earthquakes. His views found many disciples and formed the basis of the *theses of the school of Vulcanists or Plutonists.*

The fundamental truths of geology were subsequently sorted and crystallised by Charles Lyell, a Scotsman, and in 1830–33 embodied in his monumental *Principles of Geology*, which from the first met with extraordinary success and at once placed the author in the front rank of geologists.

Lyell's *Principles* is still unrivalled as an exposition of the elementary processes of denudation and rock-formation, of earthquakes and volcanic phenomena. Since his time stratigraphical geology has been enriched by the work of Sir Henry T. de la Bêche, Sir Roderick Impey Murchison, Sir Andrew C. Ramsay, Professor A. Sedgwick, Professor John Phillips, Sir Joseph Prestwich, Professor C. Lapworth, Sir Archibald Geikie, Professor W. Judd, Professor James Geikie, and other English geologists of note. At the present time the high traditions of British geology are being worthily maintained by many workers, most of whom are associated with the Universities and Geological Survey of Great Britain. It is not always easy to assess the work of our contemporaries at its true value. To do so requires the perspective of time, unhampered by local or personal prejudices. We are now able to see that, apart from the founders of British geology whose names appear above, geology as a world science owes much to such men as John Kidd, Professor of Chemistry at Oxford (1805–10); his successor, William Buckland, who taught geology and mineralogy; Robert Jameson, Professor of Natural History at Edinburgh (1804–1854); Dr G. A. Mantell; G. Poulett Scrope; A. von Humboldt; W. Herschel; Charles Darwin; and Herbert Spencer. The work of the founders for the most part concerned itself with the collecting and sifting of the field evidence relating to the stratigraphical succession, with the chronological procession of life and the division of the geological record into eras, periods, and epochs.

Though engrossed with the building up of the geological succession of formations on a palæontological basis, the early workers found time to speculate on questions of academic interest.

Lyell explained volcanic eruptions as due to the water and gases impregnating subterranean reservoirs of molten rock-material; and traced climatic variations to changing distribution of land and water, to ocean currents and accumulations of ice in the polar regions and alpine chains.

De la Bêche,[1] with a prevision far in advance of his time, propounded the view "that the foldings of the mountains of South Wales correspond to a complicated lateral pressure."

Murchison and Lyell, in their paper "On the Excavation of Valleys" (1829), while showing the power of rivers to excavate valleys, recognised that many valleys primarily owe their origin to tectonic causes.

As his interest in dynamical geology deepened, Murchison devoted much time to the discussion of tectonic problems. He explained the origin of the mountain-structure of Wales as the effect of subsidence and consequent crumbling of the crust arising from the Earth's contraction, thereby anticipating the more modern view of geo-tectonics.

Prestwich made a detailed examination of the Tertiary basins of Hampshire and London (1846–55), and to him we owe the main subdivisions of the Eocene strata of England.

Ramsay, who succeeded Murchison as Director of the Geological Survey of Great Britain, showed that on a subsiding coast the waves would cut away the cliffs as the sea advanced, and in time form a platform, which he called a *plain of marine denudation.*

Generally the years from 1800–1850 were devoted to the arranging of the chronological succession on a palæontological basis. From 1850–1870 the missionary spirit was abroad, and geological workers spread themselves far and wide, collecting fossils to verify the newly established geological column, and mapping new areas. Discovery was in the air. A rich harvest was gathered in, and many unknown but eager workers soon rose to great eminence.

At the time William Smith was mapping the Jurassic area of South England, a Scot, William Maclure, the father of American geology, was carrying on his geological survey of the United States. After two years' work he completed the first map and memoir of the geology of the country.[2] Single-handed, and in adverse circumstances, he pursued his researches in every State and Territory of the Union, and in the course of his wanderings crossed and

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[1] *Memoirs of the Geological Survey of Great Britain*, vol. i. p. 221, 1846.

[2] *Trans. Am. Phil. Soc.*, vol. vi., part 2, 1809.

recrossed the Allegheny Mountains no less than fifty times.[1] His map showed in different colours the distribution of the main geological features, from the Mexican Gulf to the Great Lakes, and from the Atlantic coast to the plains of the Mississippi. His grouping of the formations was conceived only on the broadest lines. And Horace B. Woodward[2] pays but a merited tribute to the general accuracy of the work of this great pioneer when he compares Maclure's map with that of Bailey Willis (1903), which embodies the researches of a century.

Among the founders of American geology we have Benjamin Silliman, Amos Eaton, H. H. Hayden, J. J. Bigsby, Edward Hitchcock, Ebenezer Emmons, M. Toumey, D. D. Owen, C. T. Jackson, J. D. Whitney, J. W. Foster, who concerned themselves mainly with stratigraphical problems; T. A. Conrad and James Hall, both palæontologists of note; Louis Agassiz, whose study of glacial drifts and theory of a Pleistocene glaciation laid the foundation of modern glacial geology; and the brothers H. D. Rogers and W. B. Rogers, whose work on the structure of the Appalachian chain marked an important advance in the understanding of mountain structure.

Perhaps the most outstanding figure in the two decades (1840–60) is that of James Dwight Dana, who first came into prominence as geologist and mineralogist to the Wilkes Exploring Expedition (1839–42). Outside America he is best known by his *System of Mineralogy* (1st ed., 1844) and *Manual of Geology* (1st ed., 1848), both monumental works that still rank among the classics of geological literature. While geologist to the Wilkes Exploring Expedition he made important observations as to the origin of coral-reefs. One of the earliest results of his work was to establish the principle that sea-temperature influences the growth and distribution of corals. He believed that an atoll began as a fringing-reef around a high island. This, as the island subsided, became a barrier-reef, which continued its upward growth as the island slowly disappeared. When the island finally disappeared only the barrier-reef, surrounding an inside lagoon, remained. In the main his view of the origin of atolls was the same as that independently arrived at by Darwin.

Reference has already been made to Dana's observation that the greater mountain ranges border on the greater oceans in both Americas.

From 1850 onward was a period of great activity in the States and Canadian geological surveys. Among the geologists since then whose work has made more than a local influence are Sir J. W. Dawson, Sir W. E. Logan, A. R. C. Selwyn, N. S. Shaler, and J. le Conte. Dawson made many important contributions to palæontology. Much of the work of Logan was concerned with the subdivision of the pre-Cambrian complex of crystalline rocks of the Laurentian and Huronian regions.

Shaler of Harvard, a cultured teacher and keen observer, in 1866 accepted the view that the Earth's mass consists of a solid nucleus, a hardened outer crust, and an intermediate zone of slight depth in a condition of imperfect igneous fusion. He argued that while the continental folds were probably corrugations of the whole thickness of the crust, the mountain chains were but folds of the outer part caused by the contraction of the lower part of this outer shell, the contraction in both cases arising from loss of heat. Further he conceived that the subsidence of the ocean floors would tend to promote the formation of mountain chains along and parallel with the sea-borders. In 1868, he discussed the changes of level of shore-lines during the Glacial period.

American geologists who became prominent in the decade of 1870–80 are J. W. Powell, G. K. Gilbert, C. E. Dutton, Clarence King, and J. Hall, whose work in the Far West began a new era in the study of surface forms.

Hall (1882) believed that the folded Appalachian chain was due to the original accumulation of a vast pile of sediments of which it is itself composed. In his discussion of the cause of this folding, he referred to the view expressed by Herschel that sea-bottoms when loaded by accumulated sediments undergo a process of subsidence that may cause an uplift of the adjacent continental areas. Herschel's theory of mountain-structure embodies the principle now recognised under the name of *isostasy*.

Foremost among German teachers stands L. von Buch, whose most important work was published from 1820 to 1860; H. E. Beyrich (1857–96), and his great pupil Baron von Richthofen, best known to English science by his memoir on the geology of China, and his views as to the loess of that country, which he regarded as a wind-drift.

E. Kayser, another pupil of Beyrich, published a comprehensive *Text-book of Comparative Geology*, of which an abridged translation by Philip Lake was issued in London in 1893. K. G. Bischof, a contemporary of Richthofen, threw much light on the chemical weathering and corrosion of rocks by the action of meteoric waters.

Professor Albert Heim, a Swiss geologist, made important observations on mountain-sculpturing and dynamo-metamorphism, but is best known by his great work *On the Mechanics of Mountain-building*, published in 1878. His observations showed that in the Glarus Alps

[1] G. P. Merrill, *Contributions to the History of American Geology*, Washington, 1906, p. 217.
[2] Horace B. Woodward, F.R.S., *History of Geology*, London, 1911, pp. 51–52.

the sequence of strata was totally inverted over large areas. His view that there existed a double fold composed of two anticlines overthrown towards one another, was abandoned, since Schardt demonstrated that the Alps are formed by *thrust-masses* advancing from the inner side of the mountain range and pushed towards the exterior margin. Heim strongly urged the simple truth that tectonic folding is the result of horizontal pressure in the presence of a heavy superincumbent load of rock. In the main he agrees with Suess, and explains mountain-building as a consequence of nuclear contraction, followed by crustal subsidence that sets up horizontal stresses in the upper layers of the crust.

In Italy, where fossiliferous Tertiary marine strata are conspicuously developed in the foot-hills of the Apennines, and the effects of volcanic eruptions and earthquakes could not fail to impress the imagination, it is not surprising that the study of fossils and volcanic phenomena should early attract the attention of philosophical writers.

After the dark days of science (in which only the great artist Leonardo da Vinci had a full understanding for the true nature of the fossils) Brocchi, a pupil of Werner, and one of Italy's most distinguished geologists, published a monograph on the Miocene and Pliocene mollusca of the sub-Apennines under the title *Conchiologia Fossile Subapennina* (Milan, 1814). He distinguishes the secondary rocks that compose the folded mountain-chain from the Tertiary deposits on the lower slopes and plains.

Lazzaro Spallanzani, twenty years before the publication of Brocchi's monograph, carried out experiments on the problem of volcanic rock-structure. His work, and that of H. B. de Saussure, paved the way for Hall's experiments on rock-fusion, that were at a later date carried a step further by Daubrée, Delesse, and Fouqué.

Other Italian geologists of note are Antonio Stoppani, F. Giordano, first Director of the Geological Survey, Paolo Savi, Giovanni Arduino, sometime Director of Mines and an excellent stratigrapher.

In France, the famous School of Mines in Paris has long been a seat of geological activity. Among many distinguished mining engineers connected with that institution we have Elie de Beaumont (1827–74), who was the first to conceive that the slow cooling of the Earth may have been the primary cause of rock-folding and fissuring, a postulate that became the starting-point of our modern views on mountain-structure.

In 1846, Joachim Barrande published an account of the succession, stratigraphical position, and fossils of the Bohemian Silurian basin, and compared the Bohemian and British Silurian rocks. From 1852 to 1883 he published his monumental work on the Silurian system in Bohemia.

G. A. Daubrée, another French mining engineer, between 1857–61, made important observations and experiments on the action of natural waters on rocks, and on the chemical activity of thermal waters, permeability, and abrasion of rocks.

In 1883, A. de Lapparent investigated the average height of the great continents, and afterwards published his comprehensive *Traité de Géologie*, which has passed through many editions. The names of Hauy, Fouqué, Michel-Lévy, and A. Lacroix are best known in connection with petrological research.

F. von Hochstetter, of Vienna, carried out important investigations relating to tuff-cones and other volcanic phenomena. He was geologist to the "Novara" scientific expedition (1859–64); and among other valuable work he laid the foundation of the geology of New Zealand. His contemporary at Vienna, Professor Eduard Suess, by his philosophical methods of research, as expressed in his work *The Face of the Earth*, has exercised a profound influence on the more modern teachers of geology, particularly on questions relating to crustal deformation and the genesis of mountain-chains.

Since the days of Lyell, **Mineralogy, Petrology,** and **Palæontology** have gradually developed into specialised branches of geology.

William Nicol (1827), Edinburgh, was the first to prepare thin rock-slices for examination by the microscope. In 1831 he constructed the arrangement of prisms called Nicol's prisms for the examination of crystals in polarised light. The genius of Nicol was destined to mark an epoch in the history of Petrology, though the value of his invention was not recognised till H. C. Sorby visited Edinburgh a quarter of a century later.

Sorby, by his pioneer work in the microscopic examination of rock-structures, as viewed in thin rock-slices, in 1850–60, completely revolutionised the study of rocks, and at a bound raised Petrology to the rank of an exact science. Among his followers of note are Ferdinand Zirkel, H. Rosenbusch, Sir J. J. H. Teal, A. Michel-Lévy, F. Fouqué, A. Lacroix, A. Harker, J. P. Iddings, and L. P. Pirsson.

The foundation of systematic Mineralogy had already been well-established when Petrology emerged from the mists of the Neptunistic doctrines of Werner. And in no small measure this was due to the work of W. H. Wollaston, of Carl C. von Leonhard of Heidelberg, and his contemporaries, C. F. Naumann of Leipzig, and J. D. Dana of Yale.

After the significance of fossils had been disclosed by William Smith and Cuvier, Palæontology soon came into its own. The pioneer work of J. B. de Lamarck (from 1816–23), the Sowerbys, father and son (1812–45), Ducrotāy de Blainville (1824), F. von Waldheim

(*Bibliographia Palæontologica animalium systematica*, 1834), H. G. Brown (*Lethæa geognostica*, 1835–38), A. d'Orbigny (*Paléontologie française*, 1849–55), formed the basis of a department of geology, that in the hands of a long succession of workers who have for the most part specialised in the study of certain groups or families, has now attained the dignity of a natural science. The work of W. King (*Permian Fossils*, 1849–50) on Permian Brachiopods, of P. G. Deshayes, S. P. Woodward (1851–54), K. A. von Zittel, L. Agassiz, J. Phillips, F. MacCoy, H. Woodward, J. Hall, J. Barrande, T. H. Huxley, G. Bœhm, G. Steinmann, Otto Wilckens, J. W. Gregory, S. S. Buckman, H. P. Brady, S. Scudder, C. D. Walcott, Henry Woods, E. A. N. Arber, F. A. Bather, the Etheridges (father and son), F. Chapman, and many others forms a great record without which the solution of many stratigraphical problems would have been impossible.[1]

In vertebrate Palæontology the ground-work was well laid by Cuvier (1812). Then followed a description of some fossil vertebrates in Owen's *Palæontology* (1860), in Zittel's *Handbuch der Paläontologie* (vols. iii. and iv., 1887–93), in Lyddeker and Nicholson's *Manual of Palæontology*, vol. ii., 1889, and in Smith-Woodward's *Outlines of Vertebrate Palæontology* (1898).

The researches of Cuvier (1812) on fossil amphibians, and of Sir Richard Owen on the comparative anatomy of reptiles during half a century (1839–1889), gave a new stratigraphical value to orders of fossil reptiles.

The first Dinosaur, under the generic name *Megalosaurus*, was described by Professor W. Buckland in 1824, but it was not till many years later that the essential relationship of the Dinosaurs with birds was pointed out by Huxley (1868). In 1884, O. C. Marsh, an American palæontologist, published the results of his examination of Dinosaurs, of which a remarkable assemblage had been discovered in the Jurassic strata of the Western States of North America. E. D. Cope, a contemporary worker, also described many Dinosaurs from the same States. About the same time Owen described certain remarkable fossil Reptilian remains from the Triassic Karroo formation of South Africa.

The department of Geology that concerns itself more particularly with the morphology of the Earth's surface is called *Physiographical Geology*, which is not only descriptive, but endeavours to explain the origin and development of surface forms. It was recognised by early geographers, as Strabo, Seneca, and Ptolemy, that surface forms were mainly determined by the character and arrangement of the rocks ; but it was not till the middle of the nineteenth century that physiographers adopted philosophical lines of research. The United States and Canada, with their wide spaces and grand display of physical phenomena, have produced a school of brilliant physiographers, among the founders, Powell, Gilbert, and Dutton ; and later, working on the same lines, Professor T. C. Chamberlin, Professor R. A. Daly, and Professor W. M. Davis in the United States ; Dawson, Logan, Selwyn, Bell, and Tyrrell in Canada.

Powell, in his surveys of the Grand Cañon of the Colorado River and adjacent regions, first made use of the terms *antecedent* and *consequent* valleys, *base-level of erosion* and *superimposed* valleys. He pointed out that had the Grand Cañon region been favoured with a rainfall equal to that of the Appalachian country, the entire region might have been reduced to a base-level, which would be the base-level of the sea.

Gilbert, in 1877, in his *Geology of the Henry Mountains*, was the first to establish the fundamental laws of river-erosion. He clearly demonstrated the backward progress and base-levelling effect of fluviatile erosion, and traced the relationship existing between the gradient of a river-bed and the erosive power of a river. C. Dutton, in his memoir on the geology of the Colorado Cañons, and W. M. Davis, in Pennsylvania, corroborated Gilbert's results. Professor Davis, following Rütimeyer's method, demonstrated the different stages in the development of a valley, and formation of the *peneplain* of pluvial erosion. In his more recent writings he has crystallised our present knowledge of surface-forms on the basis of genetic principles. What Davis did for English students had already been done for Continental readers by Professor A. Penck in his *Morphologie der Erdoberfläche*, published in 1894.

In the nineteenth century National Geological Surveys were established in most civilised countries, primarily for the promotion of the mineral industry. *Mining* or *Economic Geology* as a science dates from 1860. Before that, the views held by geologists as to the genesis of ore deposits was nebulous and often fantastic.

The Ordnance Geological Survey of Great Britain was established in 1835 with De la Bêche as the first Director. Then followed the appointment of Logan in 1842 as Director of the Geological Survey of Canada.

In France the Geological Survey has always been carried on by mining engineers connected with the Paris *École des Mines*. Official geological surveys were organised in Austro-Hungary in 1849, under W. von Haidinger ; in Finland (1865) ; Norway and Sweden (1858) ; Switzer-

[1] A most useful bibliography of palæontologists and their work will be found at the end of *Palæontology* (Invertebrate) by Henry Woods, Cambridge University Press.

land (1859); Belgium (1860), under Dupont, who excavated twenty-three fine skeletons of Iguanodon near Bernissart, and constructed a map of the Belgian coal-fields; and in Italy (1877). In 1879 the State Geological Surveys were united in the present United States Geological Survey under Clarence King as first Director. In Germany official surveys have been established by the single states, the most important in Prussia. Nearly all these surveys publish geological maps on the large scale of 1 : 25,000.

Among writers on Mining Geology in Europe are von Cotta, Posepny, Vogt, Beck, Beyschlag, Davies, de Launay, Michel-Lévy, Phillips, Collins, Gregory, Park, and Finlayson; and in America, Van Hise, Emmons, Le Conte, Kemp, Lindgren, Ries, Weed, Foster-Bain, Rickard, Coleman, Knight, Tolman, Brock, Rogers, Goodchild, Miller, Irvine, Winchell, and many others.

By the earlier writers, ore-deposits were arranged on a morphological basis; but the later writers have attempted to classify them in accordance with their supposed origin. The introduction of petrological methods of research, and the demonstration of the principles of metasomatic replacement have led to a truer conception of the genesis of ore-deposits than formerly existed. Field investigation has shown that most ore-deposits are more or less intimately associated with igneous rocks. It is now recognised that orogenic folding is usually accompanied by magmatic intrusions; and hence we may postulate that the great periods of diastrophic deformation were followed by vein-filling and ore-formation.

CHAPTER III.

THE DENUDATION OF THE LAND.

Denudation Defined.—By *denudation*[1] is meant the wearing away, wasting, or breaking up of the surface, whereby the general level of the land is lowered. It therefore embraces the work of all the agents of wear and tear.

Erosion refers to the more active and obvious wear and tear carried on by the sea, by streams, rivers, and glaciers, and it is embraced within the general term *denudation.*

The principal agents of denudation are:

(*a*) Air and wind.
(*b*) Rain.
(*c*) Frost.
(*d*) Streams and rivers.
(*e*) Glaciers.
(*f*) The sea.

Denudation that takes place above sea-level is termed *subaerial,* and that which takes place below sea-level, *marine.*

In a general way we may say that *air, rain,* and *frost* act upon the dry land, decomposing, softening, and breaking up the surface of the rocks. The joint action of these agents is usually spoken of as *weathering,* which is partly chemical and partly mechanical.

The material loosened by weathering gradually finds its way under the influence of gravity to lower and lower levels, till at last it gets within the reach of running water in the form of streams and rivers by which it is transported to the sea.

The general effect of weathering is to waste and lower the natural features of the landscape without material alteration of the surface forms. Like the travel of the hands of a watch, the rate of wasting is so slow that it cannot be discerned by the eye, nor even measured by instruments of the greatest precision. Only the silent wear of centuries can be gauged. Moreover, the rate of denudation is not uniform. The wall-like dykes of igneous rock that, in many places, traverse hill and dell, and the tors that so often dot moorland and plateau, are monuments of this persistent unequal subaerial weathering.

Scope of Denuding Agents.—Streams and rivers *erode* or cut away the bottom and sides of their channels; while the sea *erodes* or eats away the edge of the dry land that borders its shores.

The action of air, rain, and frost is slow and almost imperceptible; that of rivers and the sea relatively rapid and obvious. The deep river-gorge, the undermined and tumbling sea-cliff, are evidences of active erosion that cannot fail to attract the notice of even the most casual rambler among the mountains or on the seashore.

[1] In its literal sense it means to expose, or lay bare, rocks that lie below the surface. That is what prolonged denudation actually does perform. Denude comes from Lat. *de*= down, and *nudus*=naked.

The eroding action of glaciers, like that of air and rain, is silent and perhaps relatively slow; but its effects are nearly always obvious in the form of rounded contours, striated and furrowed rocks.

Most of the material removed from the surface of the land by the weathering or disintegrating action of air and rain is in the form of fine particles; while that torn from the parent-rock by the more aggressive erosion of streams and the battering of the sea, comprises larger fragments that eventually become worn into pebbles and shingle.

The products of mechanical erosion, as by running water or ice, are not decomposed but fresh, and as a rule angular in form till rounded by attrition, whereas the products of chemical weathering are decomposed. But it must be always borne in mind that chemical decomposition may set free from a rock-surface some minerals that are not readily acted on by rain or the atmospheric gases. Conspicuously among these we have quartz and mica (muscovite), which are perhaps the most abundant residuals of rock-disintegration.

The atmosphere consists of a mechanical mixture of about four volumes of nitrogen and one volume of oxygen (N 79·1, O 20·9), with traces of carbon dioxide gas (CO_2), water-vapour, ammonia, ozone, and other gases. The proportion of carbon dioxide is about 3·5 parts in 10,000. The action of the air is *chemical* and *physical*. Its chemical activity as a denuding agent is mainly due to certain inherent properties possessed by carbon dioxide and oxygen.

Ground-Water.—The source of all water running on the surface is rain or snow. Rain-water is often called *meteoric water*.

The total *rainfall* means the total precipitation in the form of rain or snow. The *run-off* means the portion of the total precipitation that runs off the surface. As a rule it varies from one-fifth of the rainfall in arid regions to one-half in dry regions. Among the many conditions that influence the run-off are the amount and intensity of rainfall, nature of soil, slope of surface, area and configuration of catchment basin, geological structure, forests, prevailing winds, climate and evaporation, and existence of storage lakes.

The cause of rainfall is not well understood, but in order to produce rain, it is certain that the temperature of the air must be cooled below the dew-point.

Ground-water is the name applied to the water that circulates in the soil and upper part of the rocky crust. In wet regions that have no dry season, the movement of the water is mainly downward under the influence of gravity; but in arid regions, evaporation causes an upward movement in accordance with the principle of capillarity.

At a certain depth below the surface the soil and rocks are saturated with water. The plain that defines this depth is called the *ground-water level*. It varies in different places, and even in the same place is found to vary with the season of the year, being higher in the winter or wet season than in the dry or summer months. Its depth usually ranges from 0 to several hundred feet, being determined by the drainage level of the country—that is, the level at which the surface streams flow. In exceptional cases the ground-water level may lie several thousand feet below the surface, as where a plateau is intersected by profound gorges or cañons.

In Flanders the variation of the ground-water level during the year amounted in some areas to 30 feet. Deep trenches that were dry in summer became flooded in winter by the rise of the ground-water.

Action of Ground-Water.—Ground-water acts mechanically as an agent of transport and erosion, as a simple solvent, and as a carrier of oxygen and carbonic acid.

Beginning with the removal of the finer particles, water, percolating along

defined tracks, forms underground channels that are usually called *blind-creeks*. Partly by erosion and partly by the crumbling of the walls and roof, these channels may become enlarged into water-courses of considerable size. When the roof collapses there is formed a depression in the ground where the water tends to accumulate. A succession of sink-holes along the course of an underground stream frequently forms the beginning of a miniature gorge, that may eventually widen out to a valley of erosion.

Ground-water charged with carbonic acid acts as a solvent of limestones in which it enlarges cracks and joints, forming underground caves and galleries. By the collapse of the roof of these underground openings, depressions called *dolinas* are formed.

In plains underlain by limestone or other calcareous rock, *sink-holes* are a common feature in the landscape. They are cylindrical or funnel-shaped cavities, usually upright in position and partially filled with sand or soil. They are due to the solvent action of water acting along joints or fissures in the limestone.

The action of water in conjunction with oxygen and carbonic acid is discussed under other headings.

WEATHERING AND SOIL-FORMATION.

Weathering Defined.—In forests, fens, and cultivated areas the surface is usually covered with a layer of black soil that may vary from a few inches to several feet in depth. Below the soil lies a clayey subsoil which may vary from a few inches to several yards in depth. As a rule the subsoil rests on, or passes insensibly downwards into, a yellowish-coloured decomposed rock, which in turn rests on the undecomposed parent-rock lying below. This succession of black soil, subsoil, rotten rock, and undecomposed rock may be often seen in sea-cliffs, quarries, and railway cuttings (fig. 1).

The depth of the decomposed yellowish-coloured rock may vary from a few inches, or a few feet, to many hundreds of feet, and is mainly dependent on the character and situation of the parent-rock.

Chemical investigation shows that the alteration, which produces what is usually called rotten or decomposed rock, is mainly due to oxidation, carbonation, and hydration; and further research shows that oxidation, carbonation, and hydration are brought about by the chemical action of rain-water percolating through the parent-rock.

Underground mining operations have shown that the oxidised belt lies more or less parallel with the contours or undulations of the surface of the land. In mining technology the oxidised ground is usually called *yellow ground*, and the undecomposed parent-rock, *blue ground*.

In a general way, two stages or phases of weathering may be recognised:

(1) *Surface-weathering*, or *Soil-formation*.
(2) *Underground-weathering, or Mass-weathering*.

The decomposition of the surface layer by the united action of rain, oxygen, carbonic acid, and the organic acids produced by decaying vegetation forms soil, which may be defined as the ultimate or extreme product of weathering.

With perhaps the exception of the organic acids resulting from the growth and decay of vegetation, the agents concerned in the mass-weathering that produces the oxidised or yellow ground, are the same as those responsible for soil-formation.

Weathering starts at the surface and progresses downward; but if rain-

water is able to find its way underground, along cracks and joint-planes, weathering may progress laterally from the walls of these passages. Hence *surface-weathering* and *underground-weathering* may go on simultaneously.

The products of weathering remain in place except on undulating ground where the subsoil and soil, under the influence of gravity, move into the hollows. For this reason soils are, as a rule, deeper in hollows than on ridges or even moderate slopes. Soils do not accumulate on steep slopes, as the products of weathering are removed by rain as fast as they form.

Weathering Processes.—By weathering is generally understood the disintegration, decomposition, and alteration of rocks, at and near the surface. The changes are extremely complex. To a large extent they are brought about by atmospheric agencies, but the activities of certain plants and animals also play an important part. As a rule, *rock-weathering* is due to chemical changes that are sometimes accumulated by physical processes.

By *physical weathering* is meant the separation of the constituent particles by the disrupting force of freezing water and hydraulic pressure. The state of fine division increases the free surface of the particles and thereby promotes chemical activity.

Chemical weathering decomposes rock-surfaces, and brings about mineralogical changes in the body of the rock, as a whole, by the alteration of the constituent minerals.

Organic weathering is partly physical or mechanical, and partly chemical. The roots of plants penetrate the interstices of rocks and by their growth exert a disrupting influence. Plants also give off carbonic acid which, in conjunction with water, dissolves certain minerals. Moreover, the decomposition of vegetable remains produces humic and other organic acids that are powerful solvents of limestone and the felspars of igneous and metamorphic rocks. Bacteria enrich soils by the formation of nitrates, that in turn react on certain mineral constituents. But the rôle they play, though important, is not yet understood.

Of all the agents concerned in *rock-disintegration* and decomposition, water is by far the most important. It finds its way into the interstices of rocks; and in places where the temperature falls below freezing it causes crumbling of the surface layers, besides shattering the rock into large and small blocks. It acts as a solvent of certain constituents, the removal of which causes the rock to crumble.

As dry gases, carbon dioxide and oxygen by themselves possess little or no chemical activity; but in conjunction with water, or moisture, they are at once transformed into the most important agents of chemical weathering and rock-alteration. The activity of the partnership is so great that they oxidise or weather rocks wherever surface water—that is, rain or meteoric water—is able to penetrate. Under the force of gravity aided by capillary action, water is able to penetrate the joint-planes, cracks, and fissures in rocks to a depth of many hundred feet below the land-surface. The contained oxygen and carbon dioxide utilise these openings as the starting-point of their attack on the body of the rock. There are few sedimentary rocks so dense and compact that they are able to resist the penetration of water throughout their mass, except perhaps marine clays and muds.

It is noticeable that while apparently compact sandstones are weathered to a great depth, clays and marls, being impermeable by water, usually escape weathering except in a superficial layer a few inches or a few feet deep. Here be it noted that marine clays should not be confused with *residual clays*. By their continuous attack from the walls of joint-planes and cracks, the upper

portion of even the densest igneous rock may become completely oxidised and altered into the plastic colloidal material called residual clay.

Climate and Weathering.—Oxygen and carbon dioxide are universal constituents of the air, but water is essential for their activity. In regions possessing an abundant rainfall, weathering is relatively rapid; in rainless regions it is slow or non-existent. Moreover, in the former the rain promotes a vigorous growth of vegetation, which becomes a powerful ally of weathering; while in arid regions vegetation is scanty or absent.

In arid regions we get *dry weathering*,[1] which is mostly physical, being mainly the result of surface crumbling arising from alternating expansion and contraction of the surface skin of rock due to variations of temperature. The characteristic brick-red colour of desert-dust, the prevailing red-stained rocks, and iron-stone pan, are evidences of oxidation that are common even where the rocks are acidic in character. In consequence of the deficiency of moisture at the surface there is a constant, upward movement of deep-seated water, laden with dissolved iron and calcium salts, that become further oxidised when they reach the surface.

Generally, seven climatic zones of weathering may be recognised:

Two **Equatorial Zones,** one on either side of the equator, characterised by heavy rainfall and warm temperature, conditions that promote vegetable growth, and consequent rapid chemical and organic decomposition of the rocks. In these zones the products of weathering usually accumulate in place to a great depth.

Two **Desert Zones,** parallel with the equatorial zones, characterised by scanty rainfall and high temperature. In these regions the transport of the crumbling particles of rock is mainly effected by the prevailing winds.

Two **Temperate Zones,** of moderate temperature, moderate rainfall, and abundant growth of vegetation. In these zones all the agents of atmospheric and organic weathering display great activity. The drainage systems are well-developed, and weathering and water-transport are, as a rule, so well-balanced that the weathered material does not accumulate in place to great depths, as in tropical regions. In cold-temperate latitudes the winter snows protect the ground and to some extent decrease the activity of subaerial weathering.

The Arctic Zones are regions of extremely low temperature where vegetable life is scanty, and rock-weathering relatively slow, being mainly physical—that is, the work of frost. Low temperature is unfavourable to chemical weathering. In the subarctic regions the winter snow protects the rocks from variations of temperature zones, while near the poles the permanent ice and snow cover the ground throughout the whole year.

These zones are fairly well defined, but in some regions there is a considerable climatic variation from the normal. This may be due to the deflection of the great oceanic currents by land areas, or to the existence of mountain-chains that obstruct the moisture-laden equatorial winds. Thus, while Labrador possesses an almost arctic climate, Ireland in the same latitude enjoys a temperate climate through the deflection of the Gulf Stream. The high plateau and mountain-terrain north of the Himalayas is wind-swept and dry, with great extremes as between the heat of summer and cold of winter, while the southern slopes are wet and jungle-covered. In Central Otago, a dry belt of great summer heat and intense winter cold lies along the east side of the Alpine chain, the moisture of the tropical winds being precipitated on the west

[1] W. F. Hume, "Professor Walther's Erosion in the Desert considered," *Geol. Mag.*, Jan. 1914, pp. 18–22.

Classification of Chemical Processes of Weathering.

The most important of the chemical processes of weathering are:

1. Carbonation by water containing CO_2.
2. Oxidation by water containing oxygen.
3. Hydration by meteoric water.
4. Aqueous dissolution, the work of rain.

The weathering of rocks is the joint work of all the subaerial agents, and hence can only take place in the upper layer of the rocky crust where these agents have free access. The hydration and oxidation brought about by water and oxygen completely alter the physical and chemical character of the whole mass, so that it may bear no resemblance to the original unaltered rock which, as a rule, lies below the weathered zone.

Weathering must not be confused with *pneumatolysis*, which is the work of the gases and aqueous vapours expelled from cooling intrusive magmas, or with *metamorphism*, which is a kind of mass-alteration that brings about the complete rearrangement of rock-formations, even though they may be many thousand feet in thickness.

Carbonation.—Let us first consider the case of carbon dioxide. This gas, like a lump of sugar, is dissolved by water and water-vapour. Even at ordinary atmospheric pressures water can dissolve its own volume of the gas. Now when water or moist air containing carbonic acid (CO_2,H_2O) comes in contact with a carbonate mineral or a calcareous rock, the carbon dioxide in the water unites with the carbonate of lime in the rock, forming a bicarbonate of lime, which is soluble in water and therefore easily removed.

In this way the surface of a limestone or calcareous sandstone is eaten away; and, as you may observe for yourself by examining a limestone cliff or ledge, the grains of sand which are not acted on by carbonic acid stand up in sharp relief on the surface of the rock, as also do sharks' teeth, that may be present.

If a calcareous sandstone is acted on, the removal of the binding medium or cement allows the grains of sand to become free, when they are easily carried away by wind, rain, or moving water.

This eating away of the rock is due to chemical solution; hence the term *corrosion* is frequently used to denote *chemical denudation*.

Carbonic acid also acts as a powerful agent in weathering or decomposing all rocks containing silicates of alumina, potash, or soda. Both potash and soda possess a greater liking or affinity for carbon dioxide than for silica, with the result that they combine with carbon-dioxide acid, forming soluble carbonates, thereby liberating the silicate of alumina and other undissolved constituents that may be present.

Perhaps one of the best examples of this mode of rock-decomposition is that seen in the rotting of granite. The three essential constituents of this rock are quartz, felspar, and mica. The felspar is a silicate of alumina and potash. The potash unites with the atmospheric CO_2, forming a soluble carbonate of potash, while the silicate of alumina remains behind to be afterwards washed away by the rain. With one important constituent removed, the surface of the rock crumbles away, liberating the quartz grains and the

a powerful weathering agent. In the case of silicates it frequently begins to act after carbonic acid has effected the initial decomposition of the mineral. When the silicate mineral contains iron protoxide (FeO), as is frequently the case, the FeO is liberated and unites with the atmospheric oxygen and water, forming the hydrated brown oxide called *limonite*, to which the rusty-brown colour of weathered rock-surfaces is due.

Oxygen also acts energetically in conjunction with moisture in the decomposition of metallic sulphides that happen to be present in rocks. The most prevalent sulphide is *pyrites* (FeS_2), the disulphide of iron which occurs in all kinds of sedimentary and in many altered igneous rocks. This sulphide is oxidised with liberation of sulphuric acid, which at once attacks the aluminous minerals it comes in contact with, forming sulphates, many of which are soluble in water and hence easily removed. In this way the disintegration of a rock may proceed at a comparatively rapid rate.

Hydration.—Many minerals when exposed to the action of moisture possess the property of absorbing a certain definite proportion of water, a process which is chemically termed *hydration*. Thus, the mineral olivine, when hydrated, becomes serpentine; and anhydrite,[1] the anhydrous sulphate of lime, changes into gypsum, the hydrous sulphate, the change being accompanied by an increase of volume amounting to 33 per cent. Hydration is one of the results of weathering, and when it accompanies oxidation is confined to the zone of oxidation.

The conditions that have brought about the hydration of deep-seated masses of peridotite (olivine) are still obscure. Possibly the alteration in this case may be the work of pneumatolytic processes.

When hydration is accompanied by increase of bulk the process may cause disruption, fracturing, or disintegration of the adjacent rocks or rock-surfaces.

Solvent Action of Rain.—The work of rain is both *chemical* and *mechanical*. By its chemical action it dissolves many of the mineral constituents of rocks, and by its mechanical action it washes away the loosened particles to a lower level. And, as we have already shown, it decomposes and oxidises rocks as far as it can penetrate.

Chemical Effects of Rain.—Water is sometimes spoken of as the universal solvent. Even when quite pure it can readily dissolve rock-salt and many sulphate minerals. When it contains dissolved salts or gases its power as a solvent is greatly increased.

The chemical effect of rain-water is only distinguished from that of moist air by its greater activity. Its dissolving and decomposing action, like that of moist air, is mainly dependent on the carbonic acid and oxygen which it gathers from the air as it falls.

Rain acts with greater energy than moist air because it brings to bear on a given place a larger quantity of carbonic acid and oxygen. Besides, by its mechanical effect it washes away the loosened particles, thus exposing fresh surfaces to be acted on by the contained gases. Moreover, the field of action of rain is wider than that of moist air; for not only does rain act on the surface of the rocks, but it also soaks into the pores and interstices, decomposing and

[1] Gr. *a*=without, and *hudor*=water.

weathering the constituent minerals as far as it can reach. It is in this way that granites, which crop out on moorlands and other low-lying situations where the natural drainage is slow, frequently become decomposed to a depth of many feet. This decomposition, as we have already seen, is the work of the carbonic acid, which attacks the felspar—the silicate of alumina and potash or of alumina, lime, and soda—with great energy. The potash (soda) unites with the carbonic acid, forming a carbonate of potash (soda) which is soluble in water. With one important constituent broken up, the other constituents are loosened. Outcrops of granite that have been disintegrated in this way can be easily excavated with a pick, and in some cases dug out with a spade.

The milky white clay that is found mixed with the loosened quartz grains and mica scales is the silicate of alumina liberated from the decomposed felspar. It is the mineral which forms the commercially valuable deposits of Kaolin so often found in the vicinity of granite outcrops.

Rain-water is always a carrier of carbonic acid; hence, when it finds its way into cracks and joints in limestone, the rock is slowly dissolved and in this way the cracks become wider and larger. The caves and underground tunnels and passages that are so prevalent in limestone formations are merely cracks or joints that have been enlarged by the action of surface-water containing carbonic acid.

Water under high pressure dissolves a larger amount of CO_2 than water at atmospheric pressure, and this greater supply of CO_2 increases the dissolving power of such waters. The water tapped by deep boreholes in limestone is often so highly charged with dissolved lime that on reaching the surface, where the pressure is relieved, the lime is precipitated as an incrustation on the pipes and launders. At the Kotuku oilfield in New Zealand, the water from No. 1 borehole rose 20 feet above the stand-pipe and fell as a spray on the boring-shed. The water was highly charged with lime, and in a few months the roof of the shed became encrusted with a layer of limestone three inches thick, while the eaves were festooned with stalactites nearly two feet long.

Rain is also a conveyor of oxygen gas. Hence we find that wherever surface-water has penetrated, the rocks are always more or less oxidised and decomposed. The most obvious effect of this decomposition is the staining of the rock a yellow or rusty-brown colour, due to the oxidising of the iron protoxide and sulphides as previously described. As may be observed in many quarries and railway-cuttings, the oxidised rusty-brown portion of the rock is usually softer and more friable than the unoxidised portion.

In the course of mining operations, rocks are sometimes found to be oxidised to a depth of 50 or even 100 feet below the surface. In some of the Kimberley diamond mines in South Africa, the oxidised zone, or what is locally called the *yellow ground*, descends to a depth of 100 feet. Below the yellow ground comes the unoxidised rock called *blue ground*.

It should here be noted that the oxidation of ferrous oxide in the presence of moisture results in the formation of the hydrous ferric oxide called *limonite*, which, as before stated, imparts its characteristic yellow and rusty-brown colours to rocks within the zone of weathering.

Weathering and oxidation are found to proceed most rapidly along joints and stratification planes, because it is along these that surface-water can most easily find its way. When the rock is crossed by two systems of joints crossing each other at nearly right angles, the only signs of oxidation in the earlier stages of weathering are confined to the walls of the cracks. As the weather-

ing proceeds the unoxidised portion gets smaller and smaller till only a core of unaltered rock is left. When the oxidation is complete no unoxidised core of solid rock remains.

Spheroidal Weathering.—A rock-mass that is intersected by two systems of joints lying at right angles to one another is obviously divided into a series of cubes or cuboidal blocks. It is found that when some ferruginous sandstones, claystones, and basalts are jointed in this way, the weathering proceeds in concentric layers around each block, the layers frequently presenting various shades of yellow or brown. When the blocks are exposed on the face of a cliff or cutting, the different layers are found to exfoliate or peel off like the successive coats of an onion. This process of weathering is termed *spheroidal weathering* (Plates V. and VI.). In the case of greywacke, granite, basalt, andesite, phonolite, and most igneous rocks, it is not uncommon to find a core of solid undecomposed rock in the centre of each spheroid.

Effect of Rain on Sulphides.—The oxidising effect of rain-water is very noticeable in the case of sulphide ore-deposits. By long-continued exposure to the action of descending surface-waters, the outcrops of iron, copper, and silver sulphide lobes are frequently oxidised and so altered as to bear little resemblance to the original lode-matter, which usually occurs at a greater depth. The iron sulphides are first oxidised to sulphates and then to oxides, while the copper is removed by the water as soluble sulphates, or is oxidised to carbonates which stain the rock green and blue.

The far-reaching effect of rain-water is well seen in the Broken Hill lead and silver mines in New South Wales, and at the celebrated Mount Morgan mine in Queensland, where the ores are oxidised to a depth of over 200 feet below the surface.

Mechanical Effects of Rain.—We will now consider the mechanical effects of rain as distinguished from that of running water in the form of streams and rivers.

The principal effect of a pelting rain is to displace the particles of rock loosened by the chemical action of the atmospheric carbonic acid. Under the influence of gravity the particles tend to fall to a lower level where they will accumulate in favourable situations; or perhaps they may find their way into some trickling stream by which they are slowly rolled downwards till they reach a river that carries them towards the sea.

Earth-Pillars.—Another well-known effect of rain is the production of what are termed *earth-pillars*. Miniature examples of these may be seen after heavy rain in many a newly ploughed field, or on the sloping bank of a newly formed road-cutting. A small pebble or flake of stone acts as a protecting cap or umbrella, so that, while the surrounding soil or clay is washed away by the rain, the portions protected by a cap remain for a time forming cone-shaped pillars.

Gigantic *earth-pillars*, in some cases attaining a height of 20 feet or more, are frequently formed in the glacial boulder clays and moraines of Scotland, Switzerland, New Zealand, and other glaciated countries.

Formation of Soil.—Soils are formed by the chemical and mechanical disintegration of rocks. In process of time the decomposed material becomes black and loamy by the admixture of organic matter mainly derived from the growth and decay of vegetation.

A large proportion of the finer particles released by the disintegration of rocks is washed by driving rains into streamlets and rivers, by which it is carried to the sea or some lake where it is spread out in the form of mud or silt. Torrential rains cause rivers to become swollen; and since such rains carry

all fine particles before them, we find that swollen rivers are as a rule mud-laden.

The angle of rest of wet clay is 16°; of sand, 22°; and of splintered rock and shingle, 40°. It is, therefore, obvious that on all surfaces flatter than the angle of rest, the products of weathering and disintegration will tend to accumulate where they were formed, except perhaps on the face of crags and steep slopes where the rocky face is exposed to driving winds and pelting rain, or the drag of winter snows.

On the loosened weathered crust such lowly forms of plant life as lichens and mosses soon establish themselves, their roots and rootlets penetrating all the crevices of the disintegrated rock-surface. The decaying vegetation produces *humic* and other organic acids which disintegrate the surface still further. Thus, as time goes on, the particles of rock become mixed with decaying vegetable matter, the mixture forming a dark-brown vegetable *humus or soil*.

The thin layer of soil (*a*, fig. 1) thus formed soon attracts grasses, shrubs, and trees which, owing to their more vigorous growth, send their roots deeper into the broken crust, and by their decay provide a larger supply of organic matter. In this way the layer of soil becomes deeper and richer, and frequently darker in colour. Moreover, in favourable places, earth-worms carry on their operations, crumbling up and enriching the soil with their castings.

FIG. 1.—Showing graduation from (*c*) rock to (*b*) subsoil, and thence into (*a*) vegetable soil.

Below the soil there lies the *subsoil*, which consists principally of comminuted rock and clayey material, frequently possessing a yellow or brown colour due to the oxidation and hydration of the iron; and below the subsoil lies the decomposed or partially decomposed rock.

The character and fertility of the soil depend on the composition and nature of the rock out of which it has been formed.

Decomposed mica-schist and calcareous sandstones produce *light* soils of great fertility; basalts, limestones, marine clays, and marls give soils that are commonly *heavy* and fertile; andesites, soils heavy and poor; granite and rhyolite, soils light and poor.

Soils Mechanically Formed.—Besides soils formed *in situ* by the chemical corrosion of the rocks by carbonic and other acids, many soils owe their existence to the mechanical effects of rain and running water. The rain washes the finer particles of rock into hollows and depressions, or carries them within the influence of some stream, by which they are borne seaward. In times of flood, when the stream or river overflows its banks, the mud-laden waters deposit a layer of silt over the adjacent lands. According to the duration of the inundation and the amount of matter held in suspension, so is the thickness of the deposit. It is in this way that the rich *alluvial* flats at the estuaries of rivers and in river valleys are formed.

Alluvial plains are to be seen in almost every country; but perhaps there is no better example of the mechanical formation of soil, or one of more historic interest or economic importance, than that of the Nile, the seasonal inundation of which deposits a fresh layer of silt over the surface of all the alluvial lands forming the delta of the river.

ACTION OF SPRINGS.

Accurate gaugings of the discharge of streams has shown that only a certain proportion of the rainfall within a given watershed is discharged to the sea. The *run-off*, as it is called, is dependent on the amount of evaporation, the steepness of the contours, the presence of forests, and the character of the rocks within the drainage area. The direction of dip of the strata in the uplands of a watershed may cause a considerable amount of the rainfall to be thrown into a neighbouring watershed.

In arid regions the run-off may not amount to more than 10 per cent. of the rainfall, and in only a few cases does it anywhere exceed 40 per cent. This means that a large quantity of the rain-water soaks into the soil and rocks, or is lost by evaporation.

Many rocks are so open or porous in texture that they are what is termed *pervious*, and rain-water slowly sinks into them till an *impervious* bed or stratum is reached. When this happens the water flows along the impervious stratum, and if this stratum comes to the surface the water issues as a spring.

Calcareous Waters.—In its slow percolation through the pores of the rocks, rain-water dissolves certain constituents and thus becomes more or less charged with mineral matter. For example, water that flows through a limestone formation is found to be *hard*, this hardness being mainly due to the dissolved bicarbonate of lime contained in the water.

What is termed the *temporary hardness* of water is represented by the bicarbonate of lime that is precipitated as carbonate of lime, when the water is boiled. The boiling disengages the molecule of CO_2, which enabled the water to dissolve the carbonate of lime, and thus permits the carbonate to be deposited as a solid incrustation in the vessel. The *permanent hardness* of water is the hardness that remains after the carbonate of lime has been precipitated by boiling. It is mostly caused by sulphate of lime, which is not thrown down by boiling.

Waters possessing a high degree of temporary hardness are injurious to steam boilers on account of the hard incrustations they deposit.

Where calcareous waters reach the surface they frequently deposit a white crust of carbonate of lime round the objects over which the water flows. This *calcareous sinter*, or *travertine* as this deposit is called, is usually porous in structure, and often contains the *petrified* remains of mosses, twigs, and various plants that grew within reach of the spring.

Stalactites and Stalagmites.—When rain-water in its underground journey through limestone has widened out a fissure to the dimensions of a cave, the slow drip of calcareous water from the roof allows the feebly attached molecule of carbon dioxide to escape once more into the air, and in this way the carbonate of lime is deposited as a thin ring. As drop succeeds drop, the ring of carbonate grows thicker and longer, in time forming a long tube which, by subsequent deposit inside, becomes solid. As the process goes on, so the pendent deposit grows longer till it forms what is called a *stalactite*, which in form somewhat resembles an icicle of frozen water.

The drops of water that fall on the floor of the cave deposit more carbonate of lime. In this way there is built up a solid pillar or *stalagmite* that in many cases unites with the depending stalactite, forming a continuous pillar reaching from the floor to the roof. Stalactitic calcareous deposits always possess a beautiful radiating fibrous structure.

Caves and underground caverns are common in limestone regions in all parts of the globe. Among the best known are the Mammoth Caves in Ken-

tucky, Wyandotte Caves in Southern Indiana, Peak Caves in Derbyshire, Dachsteinhöhle in Upper Austria, Jenolan Caves in New South Wales (Plate VII.), and Waitomo Caves in New Zealand. Many streams and rivers flow for miles in underground channels or caverns and suddenly reappear at the surface.

Ferruginous or Chalybeate Springs.—*Rain-water in its passage through rocks containing sulphides frequently becomes charged with iron salts.* When the water issues at the surface the iron, through the action of the atmospheric carbon dioxide, is converted into the ferrous carbonate. The carbonate is rapidly oxidised by the oxygen of the air into the hydrous oxide, which falls as a yellow or foxy brown precipitate. In this way are formed the limonite (hydrous peroxide of iron) veins so frequently found traversing ferruginous sandstones and altered igneous rocks. The variety of the hydrous peroxide known as *bog-iron ore* is formed in the bottom of swamps and lagoons by the same series of reactions, aided by the operations of certain species of bacteria.

Brine Springs.—The underground waters that in the course of their journey come in contact with rock-salt or with rocks impregnated with that mineral become strongly saline, and, where they appear as springs, bring large quantities of the dissolved salt to the surface. Brine derived from artificial wells made by boring is a valuable source of salt (chloride of sodium) in Cheshire in England, and Bex in Switzerland.

Mineral Springs.—These are found both cold and hot. Some are alkaline, containing carbonates of soda and potash, and bicarbonate of lime; others are acid, containing hydrochloric or sulphuric acid mostly combined with lime, magnesia, soda, and potash. Free hydrochloric and sulphuric acids are frequently present in large amount in the hot mineral waters that abound in some volcanic regions.

In regions of expiring volcanic activity hot mineralised springs are quite common. Notable examples of these are found in the Yellowstone National Park in the United States, in the North Island of New Zealand, and volcanic regions of Japan.

Geysers and hot springs frequently deposit silica or *siliceous sinter* around their vents and on the walls of their passages. In this way enormous deposits of sinter have been formed in Iceland, Yellowstone National Park, and Rotorua, New Zealand.

The silica exists in the water in the form of soluble alkaline silicates. It is deposited on reaching the surface, partly owing to the decrease of temperature and pressure, and partly owing to the atmospheric carbon dioxide uniting with the alkalies whereby the silica is liberated.

Oil Springs.—Petroleum is sometimes brought to the surface by springs and spread as a film over sheets of stagnant water. All the productive oil-wells are, however, made by boring holes to a porous stratum saturated with the mineral oil. Some of the *gushers* in the Texas, Baku, and Maikop oil-fields have yielded many thousands of barrels of oil per day.

The Work of Frost.

In countries where the temperature falls below freezing in winter, frost is always an active agent in disintegrating and disrupting rocks. The principle underlying this is the circumstance that water in the act of freezing expands in volume, particularly that which contains dissolved gases. When the expansion takes place in a sealed vessel or bomb, the pressure exerted by this expansion is almost irresistible, amounting to 2000 lbs. per square inch.

Rocks and soils are always porous and contain a good deal of interstitial water. When this water freezes, the particles are pushed a little apart. As the result of alternate thawing and freezing, the particles are forced further and further apart till they are finally broken off the parent rock. In this way the surface of porous sandstones and sandy limestones is disintegrated, crumbling away in small flakes.

The destructive effect of frost is strongly marked among the higher mountains where the winters are severe. Water finding its way into the cracks and fissures of the rocks exerts such enormous disrupting force that even large slabs are broken from the solid formation. In many regions the crests of the mountains have thus become covered with a waste of angular slabs broken up by the frosts of many winters.

Mountain slopes are frequently covered with a mantle of loose angular fragments reaching in places from the crest to the base, forming what is known as a *scree*, *talus*, or *shingle slide*. Where the rock is of a friable character, such as a claystone or slaty shale, easily acted on by frost, the scree may extend along the slope of the range for many miles; but where the rock is of a more resistant character, the scree generally takes the form of a cone which tapers to smaller dimensions as it reaches upward.

The apron of tumbled rock fragments and blocks which accumulates at the base of most cliffs and escarpments is called a *talus*.

The Work of Wind.

Next to running water, wind is the most powerful of all the subaerial geological agents. It plays a double rôle, acting as an agent of transport, and an agent of mechanical corrasion[1] or erosion.

Wind as an Agent of Transport.—Moving air in the form of wind sweeps over the land, carrying before it the particles of dust and sand loosened by the agents of decomposition and disintegration. Along the sea-coast and in deserts, the sands are blown into hummocks and ridges that frequently attain a height of 100 feet or more. Such hummocks and hills of sand are called *dunes* (Plate I.).

Blown sands are frequently piled up in lines of dunes fronting a sandy beach. Where the dunes obstruct the natural drainage to the sea it is not unusual to find chains of shallow lagoons on their inland side running parallel with the coast-line.

As a consequence of its prevalence, great hardness, and insoluble character, quartz in the form of small and large grains is the principal constituent of coastal and desert sands. As a rule quartzose sands contain hard minerals derived from the rocks in the neighbourhood. On the seaboard of Patea, New Zealand, the dunes are black in colour, being composed of ilmenite and quartz grains. In Bermuda the dunes consist mainly of coral sand, shell fragments, and Foraminifera, and hence are white.

In the rainless Sahara, Mongolia, Arabia, and Arizona, wind-borne sands cover thousands of square miles that to the traveller present a monotonous landscape of utter desolation. From the plains the sands spread to the foot-hills, and even surmount the highest chains, filling the valleys to the crests of the bounding ridges. In arid regions vast piles of sand are moved to and fro by the prevailing winds. As will be demonstrated later, the layer of shimmering heated air on the surface and the blistering Sun overhead are important agents of disintegration in countries where arid conditions prevail.

In moist climates the travel of wind-blown sand is relatively slow, and by

[1] See footnote, p. 41.

Sand-Ripples.—Ripples, somewhat similar in appearance to those formed by wave-movement, are frequently formed on dunes by the action of the wind. It has been proved experimentally that ripples are not formed where the sand-grains are of uniform size, but only where there is a mixture of fine and coarse grains. This depends on the principle that where the wind strikes on an obstacle an eddy is formed on its lee-side. Rippling takes place when this eddy in the lee of the larger grains is of sufficient strength to lift the smaller grains.

On the windward side of the large grains a long gentle slope is formed, up which the grains travel. At the summit the larger grains are arrested by the eddy and build up the ridge of the ripple, while the vertical motion of the eddy scours out a trough in the loose sand at the foot of the steep slope (Plate I.).

The ripples are continually moving forward, the larger grains falling over the crest of the ridge, thereby assisting to build up the advancing steep lee-slope on which the grains assume the natural angle of rest.

Two series of ripples may be formed in desert regions where the prevailing winds have winnowed out the finer particles, leaving only the coarser sands. The larger or primary ripples occur in parallel lines, and resemble miniature sea-waves. They are formed of the coarsest particles such as can only be moved by the strongest winds. The smaller or secondary ripples move forward under the influence of the gentle breezes. They may lie parallel to, or run obliquely across, the trend of the primary sand-waves according to the direction of the wind (Plate I.).

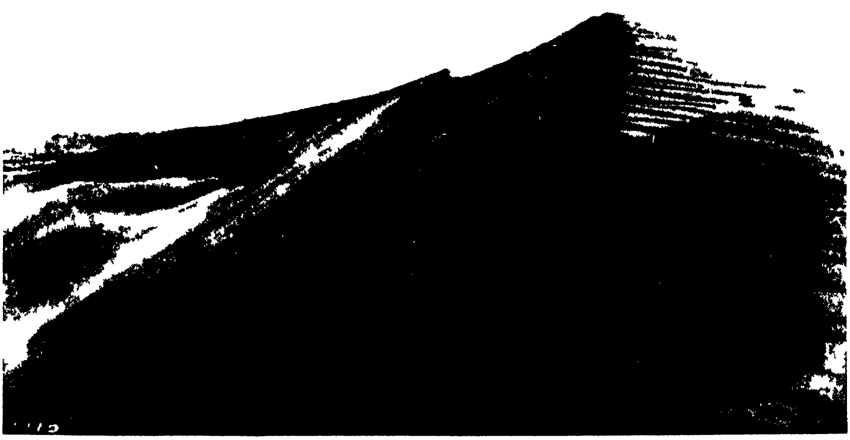
Sand-ripples and sand-waves always lie at right angles to the direction of the wind that produces them.

In sand dunes that have been cut through by watercourses, the sand is often seen to be arranged in thin well-defined layers. Bedded wind-borne sands often exhibit good examples of what is called oblique or false-bedding. This structure is so common in all accumulations of blown sands that it is considered a characteristic feature of rocks formed in desert conditions.

Mechanical Effects of Wind.—The erosive effects of wind-borne sand is everywhere present in arid regions. The fretting or abrading action of the travelling sand produces effects resembling those of a giant sand-blast. The sand wears away the rough edges of the rock hummocks that lie in the path of the prevailing winds. Rock-faces are grooved and corrugated, or worn into fantastic shapes according to the varying hardness and resistance offered by different portions of the rock. In some situations, cliffs and stacks are undercut; and in places where wind eddies are formed, miniature cirques and rock-basins may be eroded by the swirling sands (Plates II. and III.).

Notable examples of the erosive effects of travelling sand may be seen in

A WIND-RIPPLES, PRIMARY AND SECONDARY, IN COARSE SAND (CROMWELL DUNES) (After L Cockayne)



B GENERAL VIEW OF WANDERING DUNE, FORMERLY GOOD GRAZING LAND, SHOWING RIDGE AT SUMMIT OF SAND FALL (After Cockayne)

the planting of sand-binding grasses and shrubs it can frequently be checked; but in arid regions a powerful dust-storm of even short duration, as the writer has found, is capable of displacing vast quantities of sand and dust that overwhelm everything in their course. In desert regions the wind is, therefore, an important sorting and transport agent; but the manner in which it operates is fundamentally different from that of streams and rivers. These always flow in one direction, and hence they carry their load from a higher to a lower level—that is, seaward or into an inland basin; whereas the desert winds travel backward and forward across the arid wastes, moving the sand and dust from place to place within the arid zone itself. In this way sand may accumulate in desert places till it occupies the whole landscape, thereby creating in the observer's mind the erroneous impression that the denudation of arid regions is excessively rapid.

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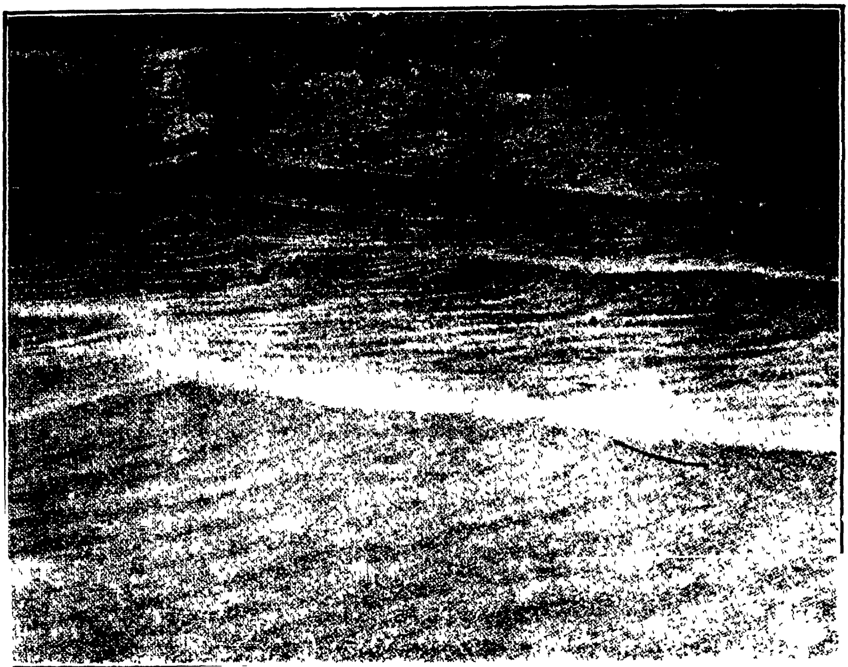
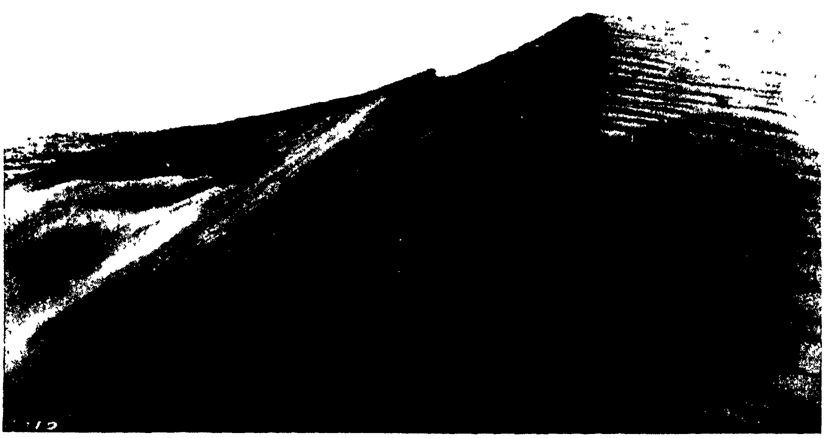
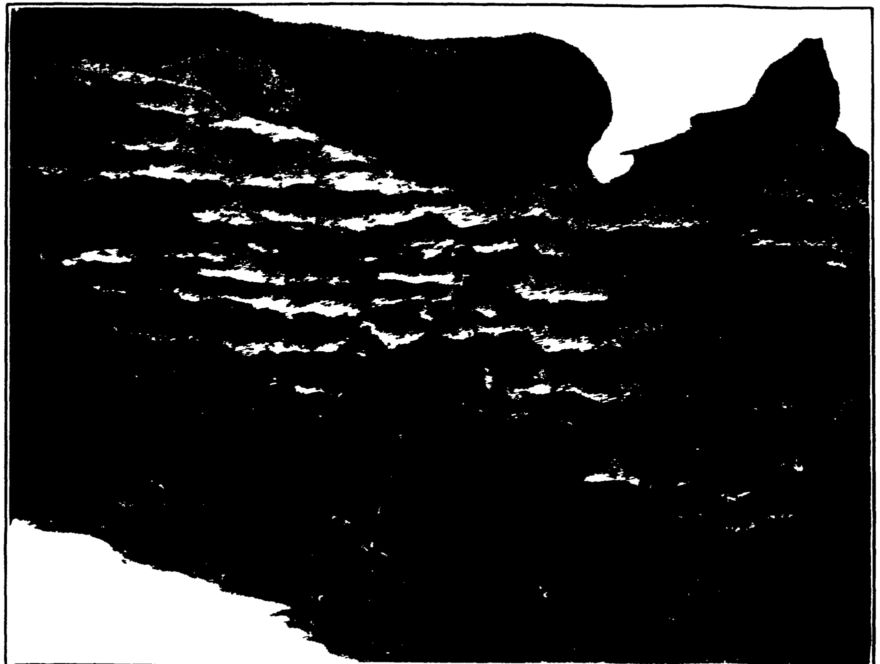


A. WIND-RIPPLES, PRIMARY AND SECONDARY, IN COARSE SAND. CROMWELL DUNES. (After Cockayne.)



B. GENERAL VIEW OF WANDERING DUNE, FORMERLY GOOD GRAZING-LAND, SHOWING RIDGE AT SUMMIT OF SAND-FALL. (After Cockayne.)

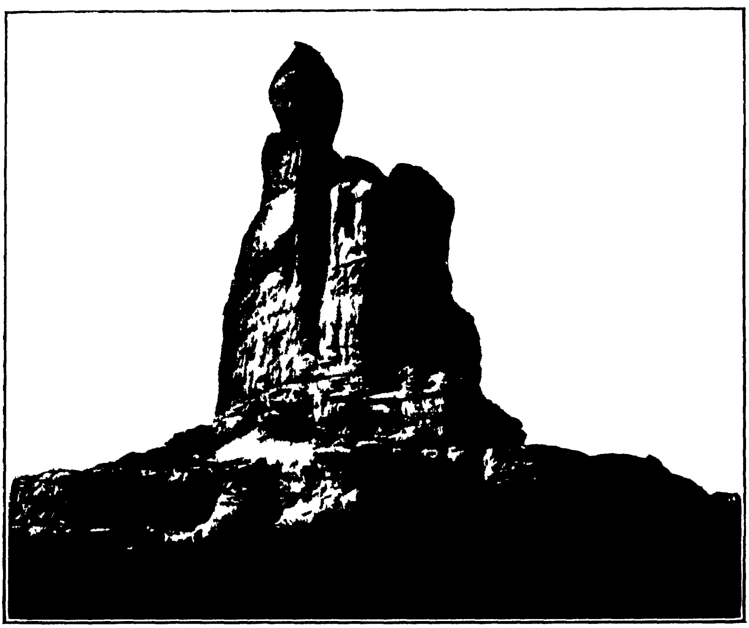
To face p. 34.] [PLATE II.



Photo, L. Cockayne.]

ROCK EROSION BY WIND-BORNE SAND. REEF POINT, NORTH-WEST AUCKLAND.

Cross bedded Sandstone of Castle Formation at Red Buttes Wyoming eroded by Wind borne Sand



Pulpit Rock, South of Laramie, Wyoming (U S Geol Survey) Erosion by Wind borne Sand

To face page 34]

[PLATE IV

SAND WORN PEBBLES OF AUGITE ANDESITE WAITOTARA NEW ZEALAND

Lower Egypt, Western Arabia, on the Great Western Plateau of Australia, and in Southern California.

The sand-erosion suffered by the Sphinx and some ruined temples in Egypt would tend to show that the action of moving sand is relatively rapid.

In places where pebbles lie on a wind-swept rocky platform, the pebbles in time become worn into tent-shaped forms by the sand travelling first from one side and then from the other. From their prevailing three-cornered form these pebbles are known as *Dreikanter*.

An instructive example of sand action is represented in fig. 2. Another is to be seen on the pebble-scattered limestone platform on the sea-coast at Nukumaru, New Zealand, where hundreds of sand-worn pebbles are to be seen in every stage of erosion (Plate IV.).

Owing to geographical changes, the sand-worn pebbles may become buried in piles of drifting sand, or even in fluviatile or marine deposits. Dreikanter

FIG. 2.—Showing sand-worn, mushroom-shaped rock of millstone-grit, Yorkshire. (After Phillips.)

are known from a number of older deposits, as the pre-Cambrian Torridon Sandstone of Scotland, Trias of England, and Pleistocene of Cape Cod, Massachusetts (W. M. Davis). Their occurrence is of great importance, since in conjunction with their *desert-polish* they are a proof of land conditions and wind action.

Effects of Changes of Temperature.—This is a powerful agency of denudation in regions where there is a considerable daily range of temperature. In the interior of arid continents there is frequently a range of 40° or 50° Fahr. as between the day and night temperatures. This rapid change of temperature through alternate expansion and contraction introduces enormous stresses in the surface skin of the rocks. The effect of these stresses is to cause the surface of the rocks to peel off in thin irregular flakes. In this way cliffs are slowly disintegrated and the surface of arid plains loosened.

The action is similar to that which takes place when a plate of steel is exposed to the oxidising influence of moist air. A film of rust—that is, oxide of iron—forms on the surface. In a short time the alternate expansion and contraction of the plate, due to changes of temperature, cause the rust to peel off in irregular scales. This exposes a fresh surface to the oxidising agent. A new skin of rust forms, soon to be displaced in the same way as the first. Thus,

in course of time, the plate becomes corroded and pitted; and the thinner the plate becomes the more rapidly does the oxidation proceed.

The primary condition of aridity is restricted rainfall, which may be modified by latitude and altitude, topographical barriers, and prevailing winds. In such regions, the ratio of the annual rainfall to the possible evaporation is an important feature.

The low relief of arid desert regions and the vast accumulations of loose sandy material that generally abound on them would tend to indicate that *surface-stress* due to changes of temperature must rank among the most active of the processes of disintegration.

Summary.

From what has been said in the foregoing pages we find that the general effect of the different agents of denudation is to waste the surface and wear the edge of the dry land.

The agents of subaerial denudation range themselves in two main groups, namely: those which operate slowly and almost imperceptibly, but none the less surely; and those that work energetically, but in a narrower field.

The first group includes air, rain, and frost; the second group, streams, rivers, and the sea. In this chapter we have only dealt with the first group, and in a general way we may summarise their work as follows:—

(1) Moist air and rain decompose the surface of rocks by dissolving or breaking up certain constituents, or by removing the cementing matrix.

(2) The principal agent in this process of decomposition is atmospheric carbon dioxide acting in conjunction with water.

(3) The minerals principally acted on by aqueous solutions of carbonic acid are aluminous silicates containing such bases as potash, soda, lime, or iron. These silicates are found in all igneous rocks, and in many sandstones and metamorphic rocks.

(4) The rocks removed or broken up by the direct dissolving action of carbonic acid are limestones of all kinds and calcareous sandstones.

(5) The decomposition of a constituent mineral or the removal of the cementing medium permits the rock to crumble up or become disintegrated.

(6) The yellow and rusty-brown colour of soils, clays, and weathered rocks is due to the oxidation of the iron present in the silicates, or to the oxidation of sulphides, or of magnetite, the black magnetic oxide of iron.

The oxygen contents of the three principal oxides of iron are:

		Ratio. Iron.	Ratio. Oxygen.
Protoxide	FeO	1	1
Magnetite (Protoperoxide) . . .	Fe_3O_4	1	1·25
Red or brown Hæmatite (Peroxide) .	Fe_2O_3	1	1·50

In the presence of moisture the atmospheric oxygen soon converts the protoxide and magnetite into the peroxide. In this way rocks are weathered wherever surface water can find its way.

(7) In the interior of arid or rainless regions, the changes of temperature as between day and night disintegrate the surface of the rocks by

Horizontal Joints and Concentric Weathering in Granite, Middle Granite Quarry, near Woodstock, Maryland (U. S. Geol. Survey.)

Spheroidal Weathering of Ordovician Chert, Missouri
(After Ball and Smith.)

Photo by O. Trickett.]

MAFEKING GROTTO, JENOLAN CAVES, NEW SOUTH WALES

alternate expansion and contraction, in the same way as scales of rust are thrown off steel plates and rails.

(8) The wind piles up loose sand into dunes and ridges along the sea-coast, and in continental desert areas.

(9) Caves are formed in limestones owing to the enlarging of fissures by the dissolving action of the carbonic acid carried in solution by rain-water.

(10) Frost causes the breaking up of rocks by the expansive force exerted by water when it freezes.

(11) Underground water when it appears at the surface forms springs. Calcareous waters deposit carbonate of lime in caves, forming stalactites and stalagmites.

(12) Ferruginous waters deposit peroxide of iron where they issue at the surface, and also in swamps and lagoons, forming bog-iron ore.

(13) Geysers and hot mineralised springs abound in regions of expiring volcanic activity.

(14) Hot springs containing silica in solution deposit the silica where they issue at the surface, forming layers of siliceous sinter.

(15) On mountain-tops and ridges the effect of frost is to break up the rocks into slabs and angular blocks. The frost-shattered debris accumulates in places where it can rest, as a rule forming *screes* of loose angular fragments.

CHAPTER IV.

THE WORK OF STREAMS AND RIVERS.

WHEN rain falls a portion soaks into the pores and interstices of the rocks and soil, while the remainder flows over the surface in hesitating trickling streamlets. On their downward course a number of these streamlets unite and form brooklets which, lower down, grow in size and volume till they become brooks. Finally, the larger brooks unite and form rivers which may discharge their waters into the sea or a lake.

The sea or lake is the lowest level which the river can find, and is hence termed the *base-level.*

The flowing water descends, or falls, under the influence of gravity; and in its haste to reach its base-level it follows the line of least resistance. Hence in its downward course it bumps heavily against every obstruction that lies in its path. The finer particles it picks up and carries away in a state of suspension. The heavier grains are partly pushed and partly carried along the bottom in a state of semi-suspension; while the pebbles and boulders too heavy to be lifted are rolled onward, one over another. Against the rocks that are too heavy to be moved the water frets and chafes incessantly till at last the obstruction is removed, the removal being effected mainly by mechanical erosion, but also partly by chemical dissolution of the rock, or of some of its constituents. The erosion of the land and the transport of material are happenings merely incidental to the passage of rain-water to the sea.

GEOLOGICAL WORK OF STREAMS AND RIVERS.

Running water in its journey to the sea performs a double *rôle.* It acts both as an agent of *erosion* and of *transport.*

Generally we find that while the whole surface of the land is lowered by the united action of all the agents of denudation, the wear is unequal, this arising from the circumstance that the more active agents of erosion are discriminating in their operation, their activity being mainly directed towards the destruction of the softer rocks in preference to the harder.

Erosive Work of Streams.—The erosive work of streams is partly *chemical* and partly *mechanical.*

The waters of all streams contain dissolved carbonic acid and oxygen which act slowly on all the rock-surfaces with which they come in contact. The rate of dissolution of the rocks is imperceptible, except in the case of limestones and calcareous sandstones, which, in river courses, are frequently corroded into wide cavities or underground channels.

Chemical analyses have shown that all river-waters contain a certain proportion of dissolved mineral matter generally varying from 10 to 40 parts in

100,000. Of this dissolved matter bicarbonate of lime constitutes the major part.

The erosive or abrasive action of water, mechanically considered, is practically *nil*. But when running water transports particles, grains, or pebbles of solid matter, it becomes a powerful agent of erosion ; its work being strikingly seen in the excavation of deep watercourses and profound gorges.

The excavating and erosive power of rivers depends on (1) the rate and volume of flow ; (2) the character of the transported detritus ; and (3) the character and arrangement of the rocks through which the channel is excavated.

The Influence of Rapid Flow.—When the flow is rapid the excavating power is relatively greater than when the flow is slow ; for not only do the travelling sands, pebbles, etc., abrade with greater force, but a larger quantity of them is brought into action against a given place in a given unit of time. The pebbles and loose stones that are rolled onward along the bottom rub one another as well as the rocky channel, till they are reduced to the condition of fine sand or mud. By this rubbing and grinding action the sides and bottom

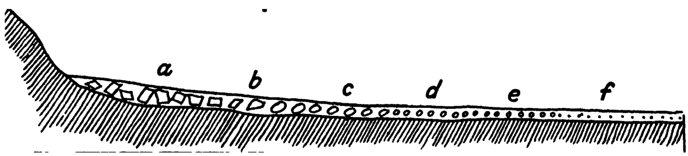


Fig. 3.—Showing graduation of river-drift.

(*a*) Zone of angular blocks.
(*b*) „ semi-angular blocks.
(*c*) „ rounded boulders.
(*d*) Zone of well-rounded gravels.
(*e*) „ water-worn sands.
(*f*) „ silt and mud.

of the river-bed are widened and deepened. Pebbles and boulders that have been rolled along the bottom of a river are always smooth and usually possess a rounded or roughly oval shape.

The rocky material in a river that traverses a broken mountainous country is commonly rough and angular near the source (fig. 3), but it becomes smoother, rounder, and smaller in size the further it is transported. In the upper part of the valley the channel is frequently piled up with large angular slabs and masses of rock that have fallen down from the heights above where they have been rent from the parent rock by the action of frost and by weathering. The waters plunge below, around, and over the obstructing masses of rock against which they wage an unceasing war. Lower down the valley the angular blocks give place to semi-angular blocks of smaller dimensions. Still lower down, only rounded boulders are seen ; and in the lower reaches these are progressively succeeded by gravels, sand, and mud.

Rivers of great length that traverse wide stretches of flat land in their lower course, such as the Mississippi, the Amazon, or the Yang-tse-kiang, transport only fine sand and silt to the sea. On the other hand, rivers with short courses and steep gradients discharge enormous quantities of coarse sand and gravel into the adjacent open seas.

The rocky debris in a river-bed is subjected to so much attrition and grinding that only the harder material is able to survive for any considerable distance from the source. The softer rocks are soon broken up and reduced to the size of small pebbles, and these after a time are comminuted to the condition of mud or silt.

If we examine the rocky material in the bed of a stream rising in a region

composed of granite, mica-schist, slate, and limestone, we shall find that near the source angular masses of all these rocks are piled up in the channel. As we proceed lower down the stream, the proportion of granite boulders will gradually increase till in a few miles they greatly predominate. Still further down, schist, slate, and limestone pebbles and slabs will become fewer and fewer till granite only is represented in the river-gravels, together with quartz pebbles and sand derived from the broken-up mica-schist or from fragments of disintegrated granite.

Thus we find that while an examination of the gravels in the lower reaches of a stream will give us evidence of the existence of certain rocks within the drainage area of the stream, it may utterly fail to give a complete view of all the rocks actually present within the watershed. There may exist at the source or in the upper reaches chalk or other soft limestone, shales, or even a whole series of Tertiary formations, none of which may be represented in the detritus in the lower reaches.

The presence of blocks or boulders of a certain rock among the gravels of a river cannot be always taken as conclusive evidence that the rock exists *in situ*, *i.e.* in place, within the drainage area of the river in question. It is not infrequently found that in regions at one time covered with glaciers, blocks of stone have been transported from one watershed to the other, and thus find a resting-place among rocks to which they are strangers. Such ice-borne blocks, or *erratics* as they are called, are not uncommon in glaciated regions.

The Erosive Effects of Floods.—All streams and rivers are subject to seasonal or periodic floods. These floods may be due to the melting of snow on the higher ranges during spring and summer, or to abnormal rainfall at any time of the year. By thus increasing the volume and depth of flow the transporting and eroding power of the current is enormously increased.

The velocity of a river, on the same slope and with a uniform cross-section, varies as the cube root of its volume ; and its transporting power varies as the sixth power of the velocity. That is to say, if the volume of a stream is increased eight times, its velocity will be doubled as $\sqrt[3]{8}=2$; and its carrying power be increased sixty-four times as $2^6=64$.

The influence which changes of velocity exercise on the transporting power of a stream or river is almost incredible, but will be in some measure realised from the following statement:—

Velocity.	Carrying power.
1	1
2	64
3	729
4	4096
5	15625

Let us take an actual case. The normal flow of the Shotover River in New Zealand amounts to 350 cubic feet per second, but the flood volume is about 9500 cubic feet per second, equal to an increase of twenty-seven times. Hence the normal velocity is trebled, as $\sqrt[3]{27}=3$. In other words, the transporting power of the river is increased over seven hundred times ; and during flood-times it can carry masses of rock weighing a ton as easily as 3-lb. pebbles when the flow is normal.

Blocks and boulders that a stream could not even move at times of normal flow may be carried down the channel for many miles, there to be left stranded as obstructions in the channel till a greater flood moves them still further down.

During floods the banks are rapidly undermined and crumble away, and in this way the river-bed is widened or new channels formed.

In 1842, a vast landslide, caused by a flood, blocked the Indus below Bunji, submerging the valley for a length of 36 miles. In 1896, a glacier blocked the Suru Valley in the Himalayas, and the imprisoned water when it burst through devastated the country below for 40 miles.

In country possessing steep slopes the rain soaks into the ground, and, accumulating on a clayey face or impervious rock, causes landslips or landslides to take place. The tumbled rocky debris forming the slide may reach down to the river torrent, by which it is soon swept away; or it may fall bodily across the river-channel, damming back the water for a time. When the pent-up flood at last breaks away it carries everything before it. Even small brooks that normally are incapable of moving anything larger than a grain of sand, in times of flood may become raging torrents capable of displacing millions of tons of rocky debris in the course of a few hours.

The rocky bed of many streams and rivers is covered with a protecting screen of gravel or sand that may be only a few inches deep, or as much as 50 feet in the case of large rivers. This sheet fills up the irregularities in the floor of the channel, and where it is deep effectually protects the bed-rock from mechanical erosion.

At times of normal flow this protecting cover is almost stationary, but during floods the material forming the upper layers is rolled down stream, its place being taken by fresh material transported from the higher reaches.

The majority of streams and rivers, for at least a portion of their course, flow over a rocky bed, free or nearly free from travelling gravel. When this happens the floor of the channel frequently exhibits many inequalities, and this is particularly the case where the stream flows over rocks of different degrees of hardness and toughness, the softer rocks being worn into depressions, while the harder form bars and obstructing reefs.

Formation of Pot-Holes.—A striking, but not uncommon, feature of many rocky river-beds is the presence of *pot-holes* of various shapes and dimensions. These holes are usually round and cauldron-like in form. They are formed by the rocking and grinding action of a hard boulder moved by the swirling eddies and acting for a long time at one point. When the pot-hole has become large enough, it is liable to be invaded by one or more new boulders which by their united action may enlarge the hole till it is many feet deep and many yards wide.

Erosive Effects of Transported Material.—The sands, gravels, and boulders carried onward by the current of a stream, besides acting on one another, also grind away the floor and sides of the channel, which is thereby gradually deepened and widened. In other words, their erosive [1] effect is both *vertical* and *lateral*, and the harder and tougher they are, the greater will be their abrasive power. The erosive effect of fine matter held in suspension is feeble, the greatest amount of excavation being effected by the semi-suspended sands, and by the gravels that are rolled and pushed along the floor.

Erosion of Different Rocks.—The excavation of soft rocks is more easily accomplished than that of hard rocks; for this reason a stream will frequently bend from its normal direction to follow along the course of a soft and easily eroded formation. In places where a river is compelled to cut through a stretch of hard rocks its channel is usually deep and narrow, the flowing water in seek-

[1] *Corrasion* is a variant of corrosion that has been used by some writers to denote the vertical excavation performed by a stream. The term does not seem preferable to the word erosion commonly used by geologists.

ing its base-level showing the same economy in excavation as the miner in cutting his water-race through the same class of ground.

Where the rock-formation is soft and comparatively easy to excavate, the channel is nearly always relatively wide and shallow.

Factors in Selection of River-Course.—The causes which have led to the selection of the course followed by rivers in their descent to the sea are various. In the main they may all be said to result from the natural tendency of running water to find its base-level by the shortest and easiest route, for brook

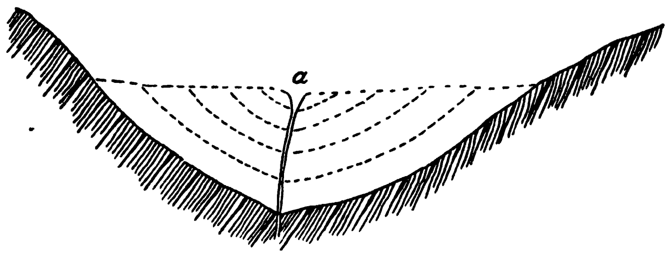


FIG. 4.—(*a*) Joint forming initial watercourse afterwards widened into a broad valley. The dotted lines show the progressive widening of the valley.

and river alike will select the route that offers the least resistance to their downward course.

If left to itself, a stream will always excavate its course in a soft formation in preference to a hard one; and follow a line or zone of shattered rock rather than cut a channel through a compact unbroken formation. In every case water will follow an opening or crack already formed rather than cut a new channel for itself.

Observations in many lands have shown that many trunk rivers follow the course of powerful faults or crustal dislocations; or run in depressions left by the uplift of parallel mountain blocks.

As we shall later find, many rocks are traversed by one and sometimes two series of more or less parallel cracks, known as *joints*. Water finds its way along these quite easily. In process of time the joints become enlarged by

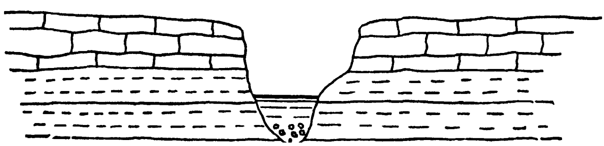


FIG. 5.—Gorge in plateau.

erosion into watercourses, and in this way we have the beginning of what may afterwards become a broad valley (fig. 4).

For the most part trunk valleys follow the course of great faults, while the direction and situation of the subsidiary or side valleys has been determined by the presence of smaller lateral faults, joint planes, or the existence of zones of soft rock.

Gorges.—Where water flows through a rift in compact rock, and the gradient

is steep, it soon, geologically speaking, excavates for itself a narrow rocky channel. Where the channel is deep, with steep sides, it is termed a *gorge*.

The gorge may be excavated through a plateau or tableland (fig. 5), or in the floor of an ancient glacial valley; or it may cut through a mountain-chain.

In recently glaciated countries there are many fine gorges that have been excavated in the floor of glacial valleys (fig. 6).

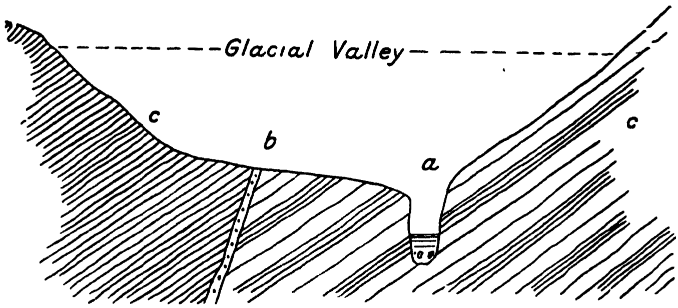


FIG. 6.—Profile of Shotover Valley, N.Z.

(*a*) Shotover R. (*b*) Shotover Fault. (*c*) Mica-schist.

Cañons.—Cañons are profound river-gorges with steep walls. They are a feature of deeply dissected plateaux where the uplift and consequent river erosion have been rapid.

Deep chasms, ravines, and gorges occur in all elevated regions, but the cañon form is almost characteristic of arid plateaux. To all deep narrow river-trenches with inaccessible walls the early Spaniards, in the Western States of America, gave the name cajon or cañon. And though the term is now popularly used in America to designate a deep valley of almost any form, it is elsewhere understood to mean any profound defile of great depth in proportion to its width.

The Grand Cañon of Colorado.—The Colorado Plateau at the south end of the Great Basin is typically a land of cañons. The Grand Cañon is the most picturesque and gigantic example of river-erosion in the world (see *Frontispiece*). The Colorado River has cut its way transversely across the Colorado Plateau, which is composed of a great thickness of horizontal sedimentary strata ranging in age from Algonkian to Early Tertiary, and resting on Archæan rocks. The upper end of the chasm is called the Marble Cañon, and the lower the Grand Cañon, but there is no gap between them.

The Marble Cañon begins at the base of the eastern terraces. At the junction of the Paria River, the Colorado River emerges from the Echo Cliffs, composed of Permian and Triassic strata. Within a mile or two it trenches into the Carboniferous rocks; and for a distance of 65 miles the depth of the chasm increases till in places it becomes 4000 feet. The Marble Cañon ends at the junction of the Little Colorado River.

The Grand Cañon begins almost where the Marble Cañon ends, and pursues a tortuous westerly course across the Plateau country. It is excavated in Carboniferous strata except for 64 miles at its eastern or upper end, and 72 miles at its lower end, where it has cut deeply into the underlying Silurian strata. The total length of the Grand Cañon is about 218 miles. The average gradient of the river is 7·56 feet per mile. The depth of the chasm varies from 4500 to 6000 feet. Its width from crest-line to crest-line ranges from 4·5 to 12 miles. In the widest part the strata are carved into buttes as high as mountains.

The Grand Cañon is a simple trench of gigantic proportions. Its walls are not diversified by lateral chasms or broken by tributary streams (*Frontispiece*).

Two phases of development may be traced when the cañon is viewed in cross-section, namely, an upper normal valley with a flat floor, and the cañon proper cut in the floor of the

upper valley. The upper valley is many miles wide and bounded by alternating steep wall and moderate slope, their edges in many places notched with short ravines.

The upper normal valley with its side valleys, ridges, and *mesas* is an evidence that pluvial conditions of denudation existed over the whole of the Plateau region before the excavation of the Grand Cañon began.

In the Pliocene period arid conditions appeared on the south-west and gradually spread eastward till desert conditions existed over the whole of the area now occupied by the plateau.

The aridity was accompanied by uplift of the whole of the Great Basin region.

After arid conditions had been established, the Colorado River directed its undivided energy to the cutting down of its channel. Though the cañon is juvenile in form, it does not necessarily follow that the river itself is juvenile. A river is as old as the mountains it drains. As soon as land emerges from the sea it becomes subject to degradation by the wasting influences of air, frost, and rain. The rain runs off the surface and forms streams that soon establish themselves in permanent courses. Having regard to the evidence presented by Powell and Dutton, we will probably not be far from the truth if we place the birth of the Colorado River in the Early Pliocene. As the ages of rivers go, the Colorado is old, but the erosive work it has accomplished bears the impress of youth.

In the juvenile stage of denudation, a plateau, or elevated plain, is trenched with deep gorges and narrow valleys. In the mature stage, the surface has been sculptured into undulating ridges and broad valleys. If the pluvial conditions that existed when the Colorado River began its work of erosion had continued till now, instead of the river flowing in a profound chasm reinforced by no tributaries we should find the plateau dissected by a spacious trunk valley with many lateral streams and wooded glades, the ensemble of mature river-erosion.

During the time the Colorado River has been employed in excavating its chasm of juvenile form, other rivers in America in rainy regions have worn their drainage area into the forms that are considered characteristic of maturity. Hence we find that the terms juvenile and mature are merely stage names that have no reference whatever to the time required to accomplish the work.

The erosion of the Grand Cañon probably began when the south end of the Great Basin stood 500 feet lower than at present. The steep walls of the Colorado trench would indicate that the uplift was relatively rapid ; but this is not quite certain, as the absence of tributary streams and the horizontal position of the strata would tend to discourage the Colorado River from wandering.

Though cañons are typically developed in arid plateaux and dry veldt country, they are also found in regions of abundant rainfall. Thus we have the gorge of the Niagara River below the Falls, and the greater chasm of the Zambesi River below the Zambesi Falls.

Waterfalls.—Where a stream or river has cut its channel in a rock-formation consisting of alternating layers of varying hardness, it frequently happens that a waterfall is formed. The softer rock is eroded at a greater rate than

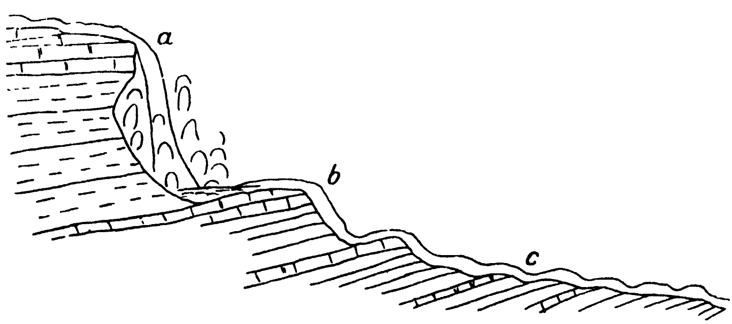


FIG. 7.—Profile of waterfall.

(*a*) Waterfall. (*b*) Cascade. (*c*) Rapids.

the harder, with the result that the stream-bed is excavated into platforms at different levels. Where the descent from one platform to another is vertical a waterfall is formed, the water falling bodily from one level to the other (fig. 7) ; and where the descent is steep but not vertical, there is frequently a

number of small waterfalls or *cascades*. In places where the slope is comparatively low, the rapidly flowing current is broken up into what is termed a *cataract* or *rapid*.

Recession of Waterfalls.—Where the strata are lying horizontal, or nearly so, and the cornice over which the water tumbles is harder than the underlying beds, the waterfall slowly recedes upstream. This recession is due to the undercutting of the cornice, which gradually crumbles away under the

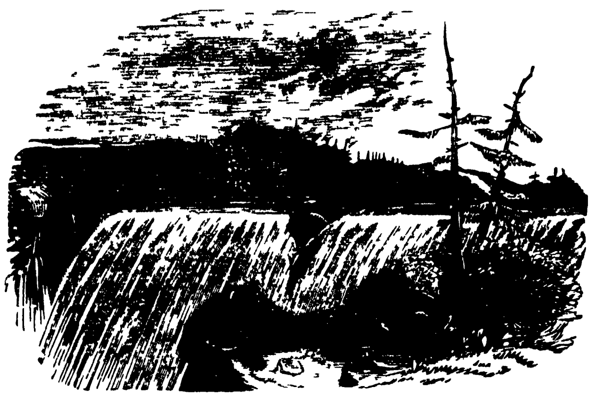


Fig. 8.—Falls of Niagara.

weight of the flowing water. In this way the gorge or ravine of the river is lengthened.

One of the most striking examples of recession is that afforded by the Niagara Falls (fig. 8), which have receded a distance of seven miles in late geological times, the rate of erosion amounting to about 4½ feet a year.

Although recession is most marked in the case of horizontal strata capped with a hard cornice, it is certain that it takes place in all waterfalls independently of the inclination of the strata. Moreover, in some volcanic regions many fine examples of retreating waterfalls (fig. 9) are seen in places where

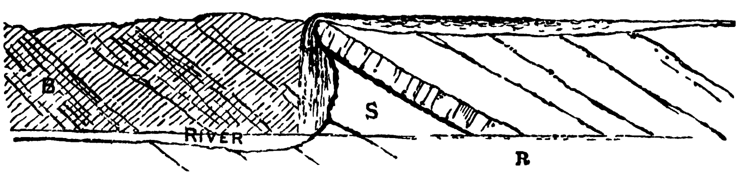


Fig. 9.—Section of river gorge, showing progress of recession.

rivers flow across streams of lava that alternate with beds of loose or only partially consolidated ash.

The Winding of Streams and Rivers.—The tendency of a rapid stream is to flow in a straight course, and in order to attain this end it will act with great energy on all obstructions that lie in its path till they have been removed. When the stream emerges from the highlands, where its gradient is steep, and passes on to flat or undulating ground, where its rate of flow is slow and its excavating power therefore relatively feeble, it is usually found to pursue a tortuous course, frequently meandering about the plain in a series of bends and loops that sometimes overlap or almost touch one another.

The stream, having only a sluggish flow and little eroding force, avoids every

obstruction it meets, whether it is a hard band of gravel or a boulder; and in this way it bends first one way and then the other.

At all times the main current is directed against the concave bank, from which it is deflected to the opposite bank. The greatest erosion, therefore, takes place on the concave bank, which during times of abnormal flood is frequently undermined and thus crumbles away. In course of time the bend becomes sharper and larger, *till in many cases the area of land between two loops is completely removed.* In this way comparatively insignificant streams are frequently found to have excavated for themselves channels of great width. *The process of excavation will be readily understood by a reference to the next figure.*

The current is directed against the bank as indicated by the arrows (fig. 10), so that in course of time the space enclosed within the stream and the dotted lines is worn away. When this has taken place the bends are seen to be sharper. As time goes on the whole of the spaces marked A (fig. 10) lying between the

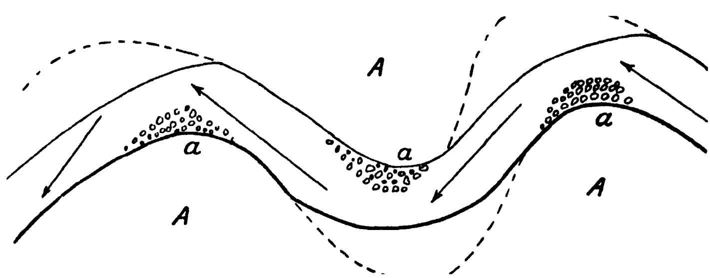


FIG. 10.—Showing winding course of stream.

loops are removed, thus forming a wide river-bed. That is, the bends gradually widen and travel downstream till the ground separating them is eventually cut away.

The velocity of the current is greatest against the concave bank and least on the convex side *a*. As a result of this the current drops a portion of its load on the convex side at *a*, where it accumulates and forms a sand or shingle bank.

The General Effect of Denudation.—The total effect of all the subaerial processes of denudation is to lower or degrade the general level of the dry land. It is obvious that if denudation continued long enough, the land would be reduced to a plain not rising much above sea-level.

We have already seen that rivers are fed with detrital matter at their sources, a large proportion of which in a finely divided form is transported to the sea. But a river possesses main tributaries, and the tributaries have their branches. These branches are in their turn fed by streamlets composed of innumerable trickling rills. A river system with its numerous primary, secondary, and tertiary branches covers the land with a network of water-courses (fig. 11), each of which carries its quota of denuded material into the trunk river, whence it is carried to the sea.

It is, therefore, obvious that in all regions drained by rivers every portion of the surface is continually under the influence of the subaerial agents of denudation, and must, therefore, in process of time, be reduced or degraded in level.

The rate of denudation will be greatest in the highlands, less in the foothills, and least in the downs and plains bordering the sea. It is greatest in the highlands because frosts are harder and the rainfall more copious than in the lowlands. The slopes also being steeper, the broken and disintegrated rocks receive more assistance from gravity in their downward course. Moreover, the gradient of the stream-beds is steeper and the transporting power of the current proportionately greater than in the low country. The degradation of the highlands may be regarded as a species of active warfare in which the rocks are shattered, broken, and ground into gravel, sand, and silt; that of the lowlands as a silent wasting of the whole surface by the slow and almost imperceptible removal of the soil by rain, partly in solution, but mainly in the form of mud or silt.

While discussing the effects of the denudation accomplished by running water, it is as well to bear in mind that the elementary function of rain is not

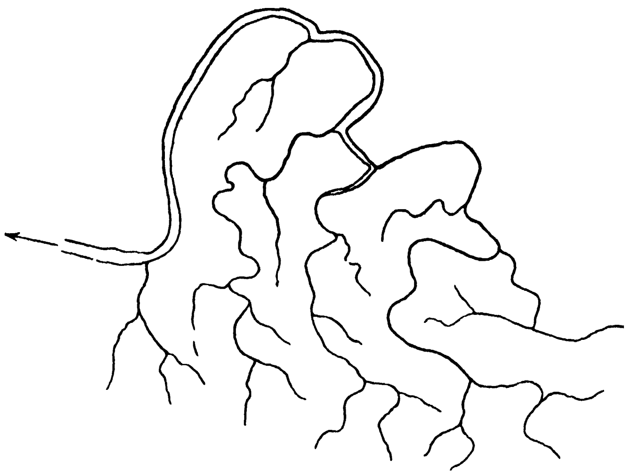


FIG. 11.—River with its network of tributaries.

to disintegrate and denude the land, but to find its way back to the ocean from which it came. The breaking up and eroding of the land over which the water flows are merely happenings incidental to the haste with which the return journey is made to the parent source.

Development of River Erosion.—When a stream begins the dissection and denudation of, let us say, a plain of deposition gradually rising from the sea, it starts life, so to speak, as a tiny rivulet. As time goes on this infant stream extends its operations. It grows longer, and by draining a larger area gets larger and stronger. With increasing age it is joined by lateral streams or tributaries which, like the parent stream, also extend their courses, and in time are supplemented by the development of branches that also possess other branches in the form of rills and trickling streamlets.

Where the slopes are steep, erosion takes place; and near the sea, where the gradients are gentle, the water-borne sediments are deposited, so that eventually the lower course of the stream is reduced to a uniform gradient. When this condition is reached the stream is said to have found its *grade-level*. If the volume of the water and the rate of erosion were uniform throughout the whole course of the stream, the profile of the river-bed would be a straight line. But the volume of all streams, except those flowing across an arid desert, increases from

the source downwards, and there is a corresponding increase in the rate of erosion till the point is reached where the gradient begins to flatten. Below this point the erosion gradually decreases till it eventually vanishes at sea-level.

The natural tendency of this differential stream erosion and sedimentation is to produce what is called a *curve of erosion* with the concave side upwards. This curve is obtained by the stream planing off the projections and filling in the hollows.

A river reaches its greatest erosive activity before maturity. But its activity possesses within it the germ of its own decay, for the more the land is degraded the flatter become the slopes of the hills and the gradients of the channels. Thus, as the land gets lower and lower, the eroding power of the river and its tributaries gets less and less, till a stage is reached when the river becomes a mere transporting agent of mud and silt. At last even this action ceases and the cycle of fluviatile erosion is complete. The decadence arising from extreme old age can only be arrested by an increased supply of water, or by an uplift of the land which will once more provide gradients that will again revive the erosive power of the running water.

If the uplift of the land begins at a late stage in the cycle of erosion, say at the time when the river is approaching the exhaustion of its denuding power owing to the land having been worn down to a nearly level plain, a second cycle of erosion will begin on the old plain ; and if no change of conditions takes place, the first-formed plain will be dissected and denuded into a second and lower *plain of denudation* or *peneplain*.

Effects of Uplift and Subsidence.—It is obvious that the progressive growth and decay of river-erosion, ending in the formation of a plain of denudation, can only take place if the land remains throughout in a state of rest, neither rising nor subsiding.

The effect of uplift occurring at any time before maturity has been reached will be to increase the erosive activity of the river, while occurring after maturity it will cause rejuvenation.

On the other hand, a subsidence of the land by lowering the gradients will accelerate the decadence of the drainage system, and if continued it will finally lead to extinction by destroying the erosive and transporting power of the river and its affluents.

Development of a River System.—The primary requirement in the development of a river system is progressive continental uplift. Moreover, the nature of the uplift is of material consequence in determining the topographical effects that may be produced by subaerial erosion acting on the surface of the rising land.

When the uplift is uniform, the ultimate effect may be the formation of a deeply dissected plateau of the Colorado type ; but if the uplift is differential, the upward movement being faster along the axial divide of the ancient land than it is along the sea-coast, the result will be the development of foothills characterised by long dip-slopes and corresponding escarpments, the long slopes being presented to the sea.

If the rate of uplift is slower than the normal rate of the marine erosion, the uprising sea-floor with its sheet of sediments will be worn down to a gently sloping plain of marine erosion that will never rise above sea-level ; but if it is faster and continuous over a long period, there will be developed a system of topographical features the form of which will be mainly dependent on the nature of the uplift, the character and inclination of the newly uplifted strata, and the climatic conditions.

Let us consider the case of a uniform uplift in an arid region. If this

region is backed by a prominent chain of mountains possessing a copious rainfall, there will be formed an arid plateau composed of horizontal strata deeply dissected by the rivers draining the neighbouring highlands. By such uniform uplift we may obtain a replica of the Colorado plateau with its profound cañons excavated by the rivers that drain the western slopes of the Rocky Mountains.

The same uniform uplift in a temperate region where the annual rainfall exceeds 35 or 40 inches will produce a maritime plain or plateau traversed by trunk rivers draining the ancient highlands, and scored by innumerable tributary streams, by which the surface is carved into a maze of narrow ridges and flat-topped hills.

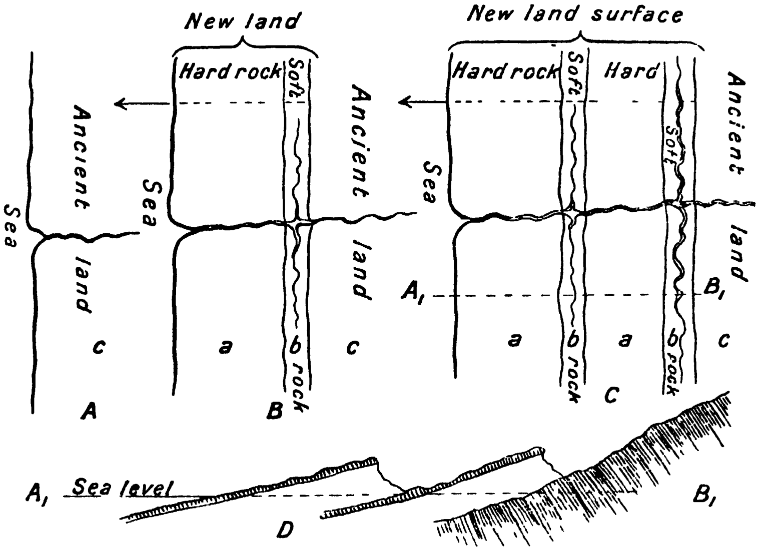


FIG. 11A.—Section on line A_1–B_1, showing development of river system arising from differential uplift.

(a) Hard stratum. (b) Soft stratum. (c) Ancient rock.
(A) First phase. (B) Second phase. (C) Third phase.
(D) Section along line A_1–B_1.

Relatively rapid uplift in a moist, temperate latitude accompanied by axial arching, whereby the strata are tilted at angles above 10° or 15°, produces a series of more or less parallel foothill ridges characterised, as already indicated, by long dip-slopes and corresponding escarpments, which are especially well-developed where the uplifted rocks consist of alternating bands of hard and soft material. Many fine examples of this type of topographical feature are found in the maritime regions of most continents where uplift has taken place in late Tertiary times.

The Actual Development.—As a starting-point let us assume an old land-surface forming highlands, and drained by a river running into the sea approximately at right angles to the general trend of the coast-line as shown in A, fig. 11A.

In the second phase, as the result of differential uplift, the sea-floor with its pile of sediments gradually rises until it forms a strip of new land running parallel with the old strand. The ancient river, that existed before the uplift

began, still finds its way to the sea ; for, as the uplift progressed, it encountered little difficulty in cutting its channel across the slowly rising truncated edges of the sediments.

The course of the river is transverse to the strike of the uprising beds, as shown in B, fig. 11A, and hence is called a *transverse* river.

As the uplift progresses, the transverse river increases in length, and its channel becomes wider and deeper.

The newly raised maritime strip of land, as shown in the second phase, now forms the foothills of the ancient highlands. The rainfall on the foothills creates small lateral tributaries that run more or less parallel with the strike, their course following the zones of softer rock. And because these streams run approximately along the strike of the uplifted strata they have been called *longitudinal* streams.

So long as the uplift continues, the transverse river and its longitudinal tributaries become longer, and their channels deeper and broader. (C, fig. 11A.)

Where the transverse river cuts through bands of limestone, conglomerate, or other hard rock, the profile of its channel is more or less **V**-shaped. In the softer zones the valley is usually broad and bounded by gentle slopes. Thus, when we trace such a river from its source to the sea, we find that it passes alternately through a succession of deep gorges and open valleys.

The type of river system which comprises a main transverse river with numerous longitudinal tributaries is most often met with in maritime regions occupied by Cainozoic or younger Mesozoic formations that were laid down marginal to the ancient strands.

Where a plain of marine sedimentation emerges from the sea as an anticlinal ridge or dome, a number of more or less parallel transverse rivers will be developed on each side of the axis of elevation. This structure is well seen in the North of England, where the eastern slopes of the Pennine Chain are drained by a number of large rivers that rise in the central divide. In the west side of the chain the symmetry has been almost obliterated by the uplift of the Lake District and the greater steepness of the Pennine Chain itself.

In the terminology adopted by some geographers, the rivers are called *consequent*, the course of which is determined by the original slope of the land. Rivers of later origin not dependent on the original topography, but by erosion acting differently on the underlying rocks according to their resistance, structure, etc., are called *subsequent.*

Striking examples of consequent rivers of this type are found draining the slopes of Mount Egmont, a beautifully symmetrical volcanic cone which rises abruptly from the sea in the south-west angle of the North Island of New Zealand. The densely wooded slopes of this cone are drained by numerous large torrential streams which radiate outward from the cone like the spokes from the hub of a wheel.

Base-Level of Erosion.—Theoretically the sea is the ultimate base-level of all streams and rivers, and is the level to which the dry land should, in process of time, be reduced, provided no change of level relatively to the sea took place during the cycle of denudation.

When a river has denuded its watershed to an area of such low relief that it has lost its eroding and transporting power, it is said to have reached its *base-level*, and the land surface so planed down is termed its *plain of erosion.* Such a plain is a *plain of fluviatile erosion.*

When elevations of harder or more resistant rock stand above the general level of the surface, such a plain of erosion is termed a *peneplain.* A peneplain

may be the work of a single river system, or of a number of rivers draining the same geographical province.

Many ancient peneplains have been elevated by faulting, or by slow crustal movement, till they have attained such a height above the sea as to form plateaux that are, as a rule, deeply sculptured by the rejuvenated *antecedent streams*—that is, the streams that existed before the upward movement began.

Cycle of Erosion.—If slow uplift begins in an area already reduced to a surface of low relief, approaching a peneplain, a new cycle of change is introduced. And if the uplift is progressive and the conditions pluvial, the *antecedent streams*, being rejuvenated by the increasing gradient, will sculpture the surface of the land into irregularities, the form of which will be determined by the geological structure, the extent and elevation of the watershed. After a time, the sculpturing will reach a maximum form of relief; and thereafter the irregularities will be gradually reduced. The first-formed gorges widen out to glens, the glens become valleys, and the valleys grow into broad meadows. The streams lose transporting power, and *aggrade*—that is, build up—their courses with detrital material; and by lateral planation build up wide flood-plains. The surface of the country becomes worn down to a condition of low relief, and the streams find their way to the sea by tortuous courses. By denudation and aggradation the region has been brought back to the subdued relief that existed before the uplift began—the base-level of erosion.

This series of changes constitutes what is called a *cycle of erosion*, or *geographical cycle*. It is based on the assumptions that the uplift ceased when the stage of maximum surface-relief was reached, and that stationary conditions followed and continued throughout the remaining stages of planation and aggradation. The Colorado Plateau and the Barewood Plateau, Otago, are good examples of elevated peneplains in process of dissection by a second cycle of river erosion.

In a general way, boldness and ruggedness of outline is an indication of the early stage of erosion; while low, gently undulating contours, in a region of diversified geological features, are suggestive of prolonged subaerial wear and tear, and a mature stage of denudation.

Peneplain of Arid Erosion.—By long-continued exposure to the disintegrating action of rain, frost, wind, and changes of temperature, the arid interior of continental areas has in some regions become worn down to a nearly level surface, or a level surface dotted here and there with hummocks and elevations of hard rock that have been able to resist the attacks of subaerial denudation longer than the surrounding country. Peneplains of arid erosion frequently occur at a considerable elevation above the sea. Among familiar examples we have the *veldt* or plateaux lands of the Transvaal and the great interior plateau of Australia.

Peneplain of Ice Erosion.—As a consequence of its ponderous movement and the rasping action of embedded blocks of stone, a thick sheet of land ice will, in process of time, wear down hills and ridges that lie in its path to the relief of a peneplain. In the region lying to the north of Lakes Superior, Huron, and Ontario, for the most part occupied by hard Archæan rocks intruded by gigantic batholiths of granite and diorite, Pleistocene ice erosion has ground down the country to a vast peneplain, the surface of which is everywhere a jumble of bare rock hummocks and *roches moutonnées*. Throughout tens of thousands of square miles the relief is lower than that of the famous Salisbury Plains in the south of England. Between Lake Superior and Hudson Bay we see what are probably the most impressive evidences of ice erosion in existence; and this leads to the suggestion that possibly peneplains of

ice erosion may underlie the ice sheets in some parts of Greenland and the Antarctic continent.

River-Piracy.—Streams have not always held the course in which they now

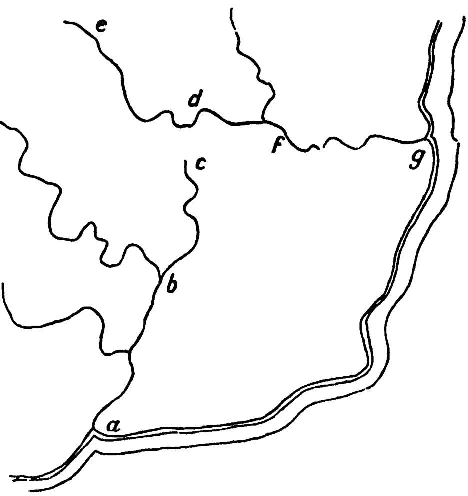


FIG. 12.—Showing progress of stream-piracy.

flow. If a stream cuts back its course and deepens its bed more rapidly than a stream in a neighbouring basin, it may work its way across the intervening

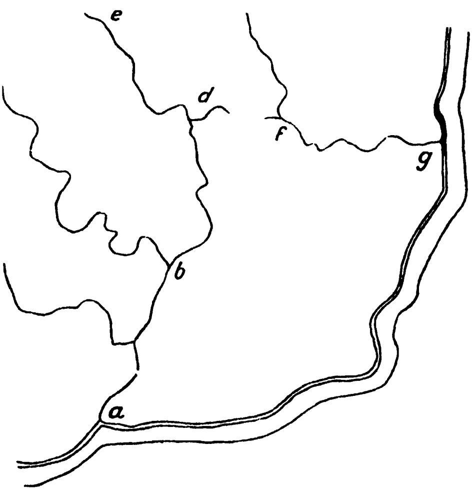


FIG. 13.—Showing stream-piracy accomplished.

divide and rob the head waters of that stream, always provided its bed is deeper than the floor of the valley that has been invaded.

If the valley occupied by stream *a b c* (fig. 12) is deepened more rapidly than the valley drained by stream *g f d e*, a tributary of the former *b c* may cut its course back to *d*, and thereby steal the head-waters *d e* of stream *g f d e*, which is then said to be *beheaded*. The invading stream is known as a *pirate*.

The beheaded stream is diminished in volume by the amount of water contributed by *d e*, while the volume of the pirate stream is correspondingly increased.

Stream *a b c* with its larger volume of flow now acquires a greater erosive power, and continues to deepen its channel faster than the beheaded stream *f g*. The result of this is that the divide at the head of *f g* is slowly shifted down the valley towards *f*, so that the drainage of the portion of the valley lying between *d* and *f* is in time reversed, as shown in fig. 13.

Protecting Effect of Basalt Flow.—In late Tertiary, that is in quite recent geological time, many of the valleys of the State of Victoria in Australia were invaded by floods of basaltic lava that filled up the river-courses and in places even overflowed the valley walls.

Since the emission of the basalts, the country has been dissected and denuded by streams, and sculptured into the existing ridges and valleys. The basalt-flows, being harder than the older slates and sandstones, have resisted the wear and tear of denudation, with the result that the old valley walls have

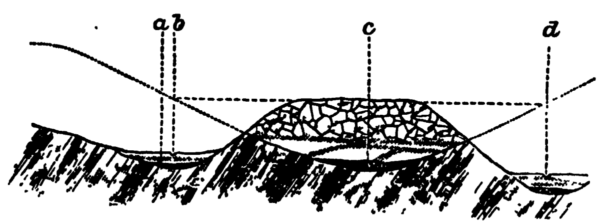


FIG. 14.—Section of Mount Greenock, showing protective effects of basalt-cap. (After A. Brough Smyth.)

(*a*) Wash-dirt in new river-course. (*b*) and (*d*) Existing watercourses. (*c*) Wash-dirt underlying basalt and marking site of ancient river.

been worn down into new valleys, while the basalts remain as flat-topped ridges as shown in fig. 14.

Rate of Denudation.—This relates to the lowering of the whole surface of the land as effected by the united action of all the agents of denudation. The data required for the computation are (*a*) the mean annual rainfall as determined by observations extending over a number of years ; (*b*) the area of the watershed ; (*c*) the annual discharge ; and (*d*) the quantity of suspended matter carried to the sea as found by experimental tests ranging over a number of years.

The margin of possible error that may be introduced into computations of this kind is always very great, mainly on account of the difficulty and expense involved in the obtaining of trustworthy mean values for the rainfall, run-off, and quantity of transported matter. Even with the best data obtainable the results cannot be regarded as other than wide approximations. When the computation is based on a few isolated observations, the results are likely to be quite misleading and altogether erroneous.

The rate of degradation of two adjacent watersheds enjoying the same rainfall may be quite different. Thus, in the area occupied by the hardest and most resistant rocks the rate will be lowest. Moreover, the mean altitude above the sea, steepness of contour, and climate must be included among the many conditions that may tend to modify the waste of the land.

The Mississippi has been estimated to lower its basin 1 foot in 5400 years, and the Danube 1 foot in 3500 years ; while the whole area of England is reduced by subaerial mechanical denudation 1 foot in about 3000 years.

All streams and rivers carry to the sea a considerable annual load of

mineral matter in solution, and although, perhaps, a large proportion of this is contributed by underground waters issuing at the surface as springs, a certain but indeterminate portion of it must represent matter dissolved on the surface by moist air and rain. The English rivers, it has been computed, lower their basins 1 foot in about 13,200 years by solution alone, but it should be noted that estimates of this kind when based on the total annual quantity of dissolved matter carried to the sea are liable to be misleading, as there seems at present to be no means of ascertaining what proportion of the dissolved matter is due to underground dissolution and what to superficial.

Constructive Work of Rivers.

Hitherto we have regarded streams and rivers as merely agents of erosion; but they are not always destructive. In some circumstances they may also be constructive. As a matter of everyday observation we know that streams and rivers gradually fill up the basins of the lakes into which they drain with piles of fluviatile drift, sand, and mud. This infilling of lake-basins is relatively rapid in the case of valley-lakes fed by torrential alpine rivers.

The heavier and coarser gravels are shot into the head of the lake, where they fall to the bottom almost at once, forming sheet after sheet of the inclined

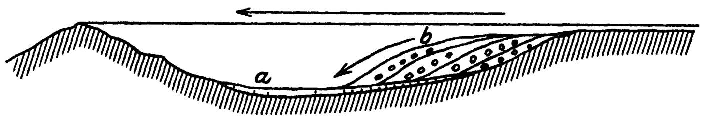


Fig. 15.—Showing filling of lake-basin by river detritus.
(a) Sand and silt. (b) Coarse drift.

beds that always mark the arrangement of fluviatile drifts discharged into still water.

The finer sands and silts are spread as a sheet over the floor of the lake, and as the infilling progresses, this sheet is covered over with the inclined coarser drifts as shown in fig. 15.

When the lake is completely filled up a *flood-plain* is formed, on the surface of which the river now flows towards the sea.

As the barrier at the lower end of the basin becomes worn down, the river with the greater slope thereby obtained once more becomes destructive. It now begins to cut away and remove the material it previously laid down, and in this way the dissection of the flood-plain is effected. It is seldom that the whole of the gravel infilling of the basin is completely removed during this period of destruction. Commonly we find that benches of gravel have escaped destruction in various places around the margin of the lake-basin, not only at the original level of the flood-plain, but also at the different levels at which the river temporarily established itself during its cycle of erosion. These gravel benches or *terraces* are a striking feature of alpine valleys in many lands.

Many great alpine lakes have been completely filled up with fluviatile drifts; and all the existing lakes are being rapidly reclaimed by the piles of detritus unceasingly shot into them by the torrential rivers that drain the neighbouring alpine chains.

The finer sediments discharged into a lake are sorted and spread out over the floor in a succession of parallel layers or beds that in a general way conform to the contour of the bottom. Such deposits are coarser near the edge of the lake and finest near the middle and towards the lower end. The remains of

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Alluvial Cones. (After C. E. Dutton, U.S. Geol. Survey.)

freshwater fish, mussels, and other molluscs, of land animals, of tree-trunks, twigs, and leaves are frequently found in consolidated lacustrine sediments.

Besides filling up lake-basins, rivers frequently discharge enormous masses of detritus into the sea, whereby in time wide tracts of land are reclaimed from the sea. Many coastal plains were built up by the confluence of river-deltas. The low-lying deltaic plains reclaimed from the sea by the Yang-tse-Kiang, Ganges, Congo, Nile, Mississippi, and Amazon cover many thousands of square miles. But the greatest fluviatile plains in the globe are the bleak tundras of Northern Siberia formed by the confluent or Piedmont deltas of the great rivers flowing into the Arctic Ocean, and the steppes of Central Russia.

A large proportion of the terrigenous material discharged into the sea is spread over the sea-floor by wave-action and ocean currents ; and in this way there have been formed, and are still forming, the wide submarine plains that fringe all the continents. These submarine plains are also confluent, and form what is called the *continental shelf*, which slopes gently seaward to the 100-fathom line. Beyond this the sea-floor descends steeply. If the sea-level were to recede to the 100-fathom line, the continents would be fringed by great maritime plains.

River-Fans.—Many lateral mountain streams at the point where they emerge from their narrow defile gradually pile up their load of sand, gravel,

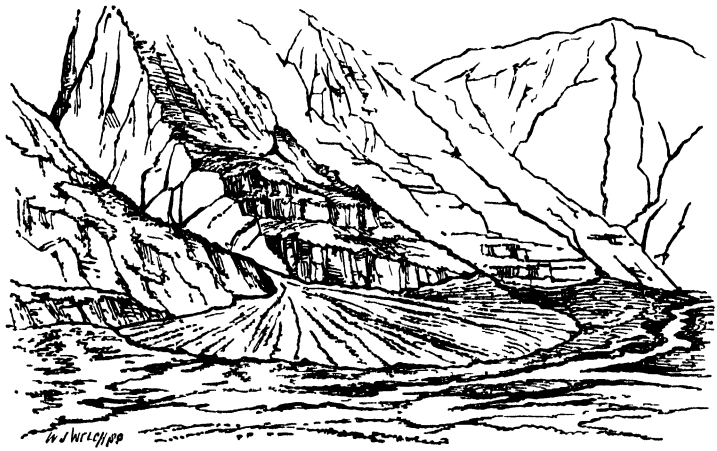


FIG. 16.—Fan at Tigar, Ladakh. (After Drew.)

and rocky detritus in the form of a wide-spreading *fan* (fig. 16), which may in time encroach so far over the floor of the main valley as to push the trunk river against the opposite wall. Good examples of river-fans may be seen in most mountain valleys where the rainfall is abundant and the denudation rapid.

Detrital fans of great extent are frequently piled up on the sea-coast by mountain streams, and a number of such confluent fans may form wide coastal plains.

SUMMARY.

(1) A portion of the rain that falls on the surface of the land soaks into the rocks and soil, but another and larger portion flows over the surface, at first forming streamlets that eventually unite and form brooks. The confluent brooks as they descend the slopes form large streams and rivers. The ultimate

destination of most rivers is the sea or a lake, while a few die out in sandy deserts.

(2) The streams and rivers in their haste to reach their *base-level, which is the sea or some large lake, wear away all obstructions that lie in their path; and sweep before them all loose particles and rocks that tend to obstruct their downward course. The steeper their slope the greater is their velocity of flow;* and the *greater their velocity and volume the greater is their eroding* and transporting power.

(3) Running water possesses little or no abrasive power; but the sand and gravel transported by it rasp and abrade the obstructing rocks which are thus worn away. The transported particles do not escape damage in this continual warfare. Like the rocks which they abrade, they also are abraded and thereby reduced in size. Moreover, the mutual wear and tear of the heavier material as it rolls over and over along the floor of the channel reduces the size of the fragments. By the attrition of the obstructions and the mutual chafing and grinding on the river-floor, we find that angular blocks are rounded, boulders are reduced to the size of pebbles, pebbles to sand, and, finally, sand to silt and mud.

(4) The heavier particles are rolled along the floor or bed of the stream, while the lighter are carried in suspension. Hence the heaviest material travels the shortest distance, and the finest the furthest.

(5) Running water in the form of streams and rivers therefore acts as (*a*) an agent of erosion, and (*b*) as an agent of transport.

(6) Soft rocks are eroded more rapidly than the hard and more resistant.

(7) When a rock-formation is crowned with a hard stratum, the wearing away of the softer underlying layers of rock enables a river to excavate a gorge or cañon.

At the point where the stream plunges into the gorge there is generally a waterfall or series of cascades. The rate at which the recession of the waterfall takes place depends on the rate at which the hard protecting cornice is undercut and worn away.

(8) When flowing across alluvial plains streams and rivers possess an inveterate tendency to deviate from the straight course. They usually meander across the plain in a winding course consisting of many loops and bends. The winding of streams is due to the slow rate of flow which enables obstructions, even those of the feeblest kind, to divert the stream from its course.

(9) The greatest erosive effect of a stream is on the concave bank, which is commonly the steeper for this reason.

(10) The total effect of all the subaerial processes of denudation is to reduce the general level of the land. If denudation were continued long enough, without compensating uplift, the land would be in time reduced to a condition of low relief not much above sea-level.

(11) A river with the aid of its affluents tends to reduce the level of the land within its drainage area. Throughout the infantile and youthful stages its denuding effect is ever increasing. Through continued denudation in the uplands and constructive work in the lowlands, the gradients become less and less till a time is reached when the sluggish waters no longer possess any transporting power. This period of enfeebled denudation is termed the *decadent* stage. When denudation practically ceases, the land having been reduced to a *peneplain* or surface of low relief, the river is said to have reached its *base-level.*

If an uplift of the land now sets in, the decadent river system is rejuve-

nated, and the more rapid the uplift the greater will be the denuding activity. In this way the peneplain previously formed will become dissected, and if denudation continues long enough, a second peneplain lying at a lower level will be carved out of the first.

(12) Peneplains may also be formed in elevated arid regions by long-continued exposure to the action of rain, frost, wind, and changing temperature. The elevated plateaux of South Africa and Australia were probably formed in this way.

(13) One of the local effects of rapid river-erosion is *stream-piracy.* When a stream cuts back its course more rapidly than a neighbouring stream, it may work its way across the divide and annex the head waters of the other stream.

(14) Sheets of basalt frequently afford effective protection to softer underlying rocks.

(15) The rate at which the whole surface of the land within a given watershed is worn away by the united processes of denudation is extremely slow. In England it amounts to about 1 foot in 3000 years.

(16) Although mainly destructive, rivers are also constructive. They fill up lake-basins, and reclaim large maritime belts of land from the sea.

The great submarine plain or continental shelf that fringes all the continents is mainly composed of terrigenous material discharged into the sea by rivers, and spread out on the sea-floor by wave-action and ocean currents.

CHAPTER V.

THE WORK OF SNOW AND GLACIERS.

THE present glaciation of the polar regions and of some alpine chains is a survival in a diminished form of the glaciation of the *Great Ice Age*, which reached its maximum severity in the Pleistocene, the period which immediately preceded the time in which we now live.

In the Great Ice Age the greater part of North America and Northern Europe was covered with an invading sheet of ice. At the same time large areas of South America, Australia, Tasmania, and New Zealand were covered with huge glaciers and ice-sheets.

The best evidences of ice-erosion are found in the regions that were overrun by ice in the Great Ice Age.

Distribution of Snowfields.—Permanent snowfields exist in the polar regions of both hemispheres, and elsewhere among the higher mountain-chains where the annual mean temperature is below the freezing-point.

Snowfields of less permanency are found in more temperate latitudes, and on the lower slopes of high ranges. They mostly disappear with the advent of spring and summer. The line above which the snow remains unmelted throughout the year is termed the *snowline*. In high latitudes the snowline comes down to the sea. In lower latitudes it gradually rises till it attains its greatest altitude in the tropics. On the northern slopes of the Himalayas it is 19,000 feet above the sea, and in the Andes 18,000 feet.

The Action of Snow.—Snow as a geological agent is both (1) *protective* and (2) *destructive*.

Protective Effect.—As a winter covering on the foothills and flat slopes, snow protects the ground and vegetation from the action of frost and rain.

Destructive Effect.—When snow accumulates on steep slopes it slides down, and in doing so dislodges obstructing masses of rock and furrows the soil, pushing all loose material before it. A good deal of broken rock and soil is also picked up by the frozen snow, by which it is carried from a higher to a lower level. In this way *screes* of angular shingle, frequently of considerable magnitude, are piled up at the lower limits of melting snowfields.

Where snowfields descend to the edge of a precipice or accumulate on steep mountain slopes, large masses become detached in spring and summer and rush down as *avalanches* that sweep trees, soil, rock, and all movable obstructions before them.

Avalanches are frequently compelled by the contour of the ground, down which they bound with crashing leaps, to follow the same route year after year. In such places they are found to have carved out for themselves deep gulches in the solid rock. Such gulches resemble gigantic chutes and are known as *avalanche slides* (fig. 17). Their sides are frequently walled in with banks of

rocky debris torn from the floor by the masses of semi-frozen snow as they thunder down to the valley below.

Streams may be blocked or partially dammed by masses of snow that have fallen from the heights above. In 1870 a large avalanche that fell from Mount Aspiring in the Alps of New Zealand blocked up the bed of the Upper

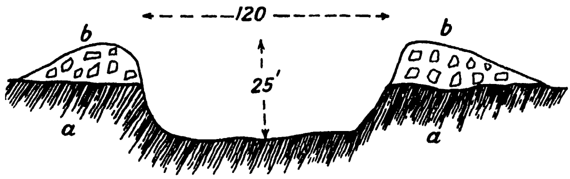


FIG. 17.—Showing cross-section of avalanche slide on slopes of Ben Ohau Range, N.Z.

(*a*) Bed rock of slate and sandstone. (*b*) Piled-up debris.

Matukituki River for several months, and even after the barrier was breached masses of ice remained in the valley for two whole years.

When the winter snows melt rapidly in spring and summer, as they frequently do in temperate climates under the influence of warm rains, they may cause a sudden inundation of the snow-fed rivers, the erosive and transporting power of which is thereby enormously increased for a time. Again, in arid regions bounded by snow-clad mountains, many of the rivers are entirely dependent for their summer flow on the supply of water derived from the melting snows and icefields at their sources.

GLACIERS AND ICE-SHEETS.

The Motion of Glaciers.—Glaciers are composed of coarse-grained glacier-ice. The snow that falls in the higher mountain-regions and accumulates in the basins between the mountain-ridges gradually becomes a fine-grained *névé*. By melting and refreezing some of the grains increase in size at the cost of the others. On their journey from the *névé*-basins down to the valleys the grains become larger and larger, and eventually the *névé* becomes transformed in glacier-ice. The snow falling in the high regions of the mountains feeds the glaciers by assuming first the form of *névé* and then of glacier-ice. Glaciers are nothing more than *rivers of ice.*

Though a crystalline substance ice behaves like a viscous body; hence, when it accumulates on the floor of a sloping valley, it descends or flows under the influence of gravity. Where the valley is wide it spreads itself out like a river, and where it is narrow it gathers itself together just as a river does in flowing through a gorge. It flows like pitch placed on a sloping plane, and accommodates itself to all the inequalities of its bed.

Many theories have been advanced by physicists to explain the flow of ice, none of them quite satisfactory. According to a view that has some support, it is supposed that, under the influence of gravity, the flow is assisted by the frequent alternations between a liquid and frozen condition that are in constant operation in some part of the mass. Under pressure ice passes into water at, or below, freezing-point; and on relief of pressure, at the same temperatures it passes from water to ice. In these constantly recurring changes there is a tendency for the ice particles, under the stress of gravity, to take up positions at lower levels. Moreover, it is found that glacier-ice

possesses a certain molecular elasticity whereby, under pressure and shear, the granules may slide over one another without losing their crystalline form.

Flow of Glaciers.—The rate of flow of water and ice is alike mainly dependent on the amount of precipitation and the gradient of their bed. Thus, while the flow of rivers may vary from 1 to 15 miles an hour according to the steepness of descent, that of glaciers is found to vary from 1 foot or less to 70 feet a day.

On account of its comparative rigidity and the enormous pressure exerted by the moving mass of ice behind, a glacier will surmount and ride over all hummocks and projecting spurs that lie in its path. A glacier is thus able to pluck blocks of rock from its bed and leave them, when it retreats, perched high up on the valley slopes. The ancient Wakatipu glacier in Otago tore off large masses of Tertiary limestone at the edge of the lake of that name, carried them nearly twenty miles and left them stranded on the schist slopes of Ben Lomond, nearly 2000 feet above the parent rock.[1]

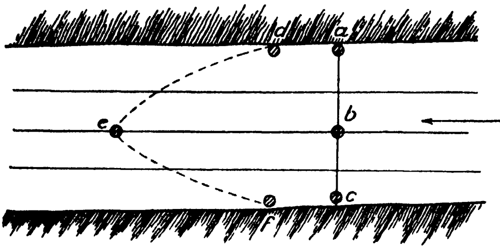


FIG. 18.—Plan of glacier showing differential surface flow. Extent of flow in middle, *b e*; and at the sides for the same unit of time, *a d* and *c f*.

The flow of a glacier, like that of running water, is greatest at the upper surface near the middle of the stream of ice, and least at the bottom and sides where the friction and drag are greatest.

A striking result of this inequality of flow is the formation of cracks or *crevasses* which are evidences of the ice yielding to tensional stresses. These crevasses either run directly across the glacier, where there is a steep descent upon the glacier-bed, or longitudinally, where the descent is moderate. Diagonal crevasses are found at the margins of the glacier and are due to the more sluggish movement where the ice is held back by the friction arising from the walls of the valley.

FIG. 19.—Longitudinal section of middle of glacier showing differential flow as between surface and bottom. Extent of flow at surface, *b e*; and at bottom, *p s*.

Steps in the bed of a glacier produce corresponding steps in the surface of the glacier. Steep steps are usually marked by numerous crevasses, which not only divide the ice into slices but even blades and needles known as *séracs*.

Crevasses commonly run transversely across the longest axis of the glacier. The differential flow is also responsible for the banded structure of glacier-ice termed *névé-stratification*, and for the semi-bedded arrangement of the rocky debris frequently seen among the material piled at the terminal face.

What is meant by differential surface flow will be easily understood by referring to fig. 18. Let us suppose that *a*, *b*, and *c* represent three blocks of stone or marks placed in a line across the glacier. It will be found that in the time it has taken blocks *a* and *c* to reach points *d* and *f* respectively, block *b* will have travelled to point *e*. Blocks *a* and *c* have moved slower than *e*

[1] Geology of Queenstown Subdivision, *N.Z. Geo. Survey Bulletin*, No. 7, p. 28.

because the flow of the ice which carried them has been retarded by the drag or friction of the rocky walls of the valley.

Referring to fig. 19, we find that while block *b* on the surface of the ice has travelled from *b* to *e*, block *p* on the bottom has in the same time travelled only from *p* to *s*, the slower rate of travel being due to the friction of the bed-rock.

It is obvious that the greater the drag or frictional resistance the greater will be the difference of flow as between the centre and the bottom and sides of the stream of ice.

Effect of Precipitation and Temperature.—The size of a glacier depends on the amount of precipitation and the temperature. With an increase of precipitation, or a decrease of temperature, the glacier will advance; and, conversely, with a decrease of precipitation, or an increase of temperature, the glacier will retreat. When the precipitation and the temperature act in the same direction there will be an acceleration of the advance or retreat.

A good example of the effect of varying precipitation is seen among the glaciers that descend from the New Zealand Alps. On the west side of the chain, where the precipitation is excessive and the slopes steep, the Fox glacier, 9·75 miles long, and the Franz Josef glacier, 8·5 miles long, descend within 670 feet and 690 feet of the sea respectively, in 43° and 44° of south latitude, corresponding to the latitude of Boston in North America and Marseilles in South France. On the east side of the alpine divide, where the precipitation is about half of that on the west side, and the gradient of the valley-floors flatter, none of the glaciers descend below 2350 feet above the sea. The terminal face of the Tasman glacier, 19 miles long, is 2354 feet above the sea, but the thickness of the ice below that level is unknown.

Greater Summer Rate of Flow.—The flow of glaciers and ice-sheets is faster during the day than at night, and during the summer than in winter. The reason for this increase is still obscure, but it probably arises from the greater temperature during the day and in summer causing expansion of the surface layers of ice as compared with what they are at temperatures below 32° F.

The lineal coefficient of steel is 0·0000063 and of ice 0·0000528. Hence, with a rise of temperature of 10° F., a strip of steel as long as the Tasman glacier, say 10,000 feet, would expand 6·3 feet, while a strip of ice the same length would expand 52·8 feet. Ice maintained at a temperature below 32° F. must expand under the influence of the sun's heat. Being free at the terminal end, the effect of expansion on glacier-ice would be to augment the normal flow due to gravity. The pressure of the valley-walls would prevent lateral expansion, and this may explain the arching of some 10 feet which is reported to take place on the surface of the Tasman glacier during the summer months.

Glacier Tongues.—Prolongations or tongues of ice that extend beyond the limits of the main body are of frequent occurrence along the margin of continental and Piedmont ice-sheets. Many good examples of these may be seen on the sea-front of the great glaciers that descend to the coast-line of Greenland, fed by the inland ice-sheet. But the most notable are found in the Antarctic region. One that has become well known in connection with Antarctic exploration is Glacier Tongue, near Hut Point, in M'Murdo Sound, South Victoria Land. It is a narrow, elongated, somewhat tabular mass of ice that stretches 5 miles into the sea. Where it rests against the land it is about a mile wide, and at its sea end about half a mile. Its height above the sea varies from 20 to 100 feet. The great depth of water obtained by soundings off the sea-end led Professor David to conclude that a considerable portion of the tongue

must be afloat.[1] Some distance further north, the Nordenskjöld and Drygalski ice-tongues extend over the sea 20 and 30 miles respectively.

Mountain glaciers that lie in basins guarded by projecting spurs or buttresses of hard rock frequently terminate in narrow prolongations or *snouts* of ice that may extend far beyond the portals of the ravine.

Distribution of Glaciers.—Glaciers occur at sea-level in the polar regions, but passing towards the equator they are found at gradually increasing elevations.

A great ice-sheet covers the whole of Greenland except a narrow fringe around the coast. Long tongues of ice descend to the sea in the valleys and sounds.

The icefields of the Antarctic are even more extensive than those of the Arctic. They everywhere descend to sea-level, and even extend over the surface of the sea for many hundreds of miles. The ice is so thick and spreads over the sea so far that the limits of the dry land cannot be ascertained. The *Great Ice Barrier* that fringes South Victoria Land is believed to have extended at one time far north of its present limits.

Valley-glaciers of great size exist at the present day in Alaska, Greenland, Patagonia, Scandinavia, Alps, Tian-shan, Himalayas, New Zealand, and Antarctic.

Among the most notable glaciers in the globe we have the following:—

- In Alaska the *Malaspina* glacier, 30 miles long, descending from Mt. St. Elias, with sea-front over 50 miles long.
- In Greenland the *Humboldt* glacier with sea-face, 45 miles long, presenting ice-cliffs from 300 to 500 feet high.
- In the Swiss Alps the *Aletsch* glacier, nearly 10 miles long, or, with snowfields, 15 miles; mean breadth, 1⅛ mile: the *Mer-de-Glace,* descending from Mont Blanc, 9 miles long.
- In the Himalayan Mts., *Siachen* glacier, 49 miles long and from 2·75 to 4·75 miles wide.
- In New Zealand the *Tasman* glacier, 18 miles, or, with snowfields, 21 miles; mean breadth, 1¼ mile.
- In South Victoria Land the *Beardmore* glacier, of unknown length, deploys on to the Great Ice Barrier.

The glaciers of the Arctic, Antarctic, and the Karakoram Mts. in Northern India are grouped as glaciers of the first order; and those of New Zealand and the Alps of the second order.

Valley glaciers are fed by *summit-glaciers* and snowfields that may slowly descend gentle slopes to the main glacier, or where the slope is steep tumble down in a cascade of broken blocks of ice, forming what is known as an *ice-cascade.*

Glaciers that push their way to the sea break up at their terminal end into masses that float away as *icebergs.*

When a number of glaciers deploy from the mountains and unite, they form what is termed a *piedmont* glacier or ice-sheet. Of such a nature is the great Beardmore glacier in South Victoria Land in the Antarctic and the Malaspina glacier in Alaska.

Confluent glaciers of this kind covered a large portion of Northern Europe and America in the *Pleistocene* or *Great Ice Age.*

The Surface Features of Glaciers.—The surface of glaciers is seldom smooth. More often it is rough, broken, and hummocky, and covered more or less with rocky debris. Moreover, glaciers that occupy valleys with steep gradients are usually crevassed in all directions by the unequal tensions set up in the body of the ice by the differential rate of flow.

Ablation of Glaciers.—The surface and terminal end of a glacier are subject

[1] *The Heart of the Antarctic,* E. H. Shackleton, ii. 284, 1909.

to the heat of the summer sun. The daily rise of temperature causes the melting of the surface ice. This surface melting or *ablation*, as it is called, may amount to many feet in the course of a single year. Desor has estimated the mean ablation of the Swiss glaciers at 10 feet a year. The surface measured rate of melting of Alaskan glaciers varies in summer from 1 to 7 inches a day, all on retreating glaciers.

The effect of continued ablation on the upper surface is well seen in the formation of what are known as *ice-tables*. These are ice-pillars capped with a flat slab of stone. The stone protects the ice below it from the direct rays of the sun, with the result that, while the surrounding ice is melted away, a pillar of ice remains, growing taller and taller till it eventually becomes too slender to support its protecting cap.

The portions of a glacier covered with morainic debris are usually higher than the portions free from debris, the former being protected from ablation by their load of rocky material.

Ablation at the terminal face causes an apparent recession of the glacier. If the rates of melting and flow are equal the glacier remains stationary. But if the rate of melting is less than the rate of flow, the terminal end advances, and if more, it recedes.

Glacier-River.—Every valley-glacier is drained by a river that usually issues from an ice-tunnel at the terminal end of the glacier. Except in the polar regions this river flows summer and winter, but the winter flow is always less than the summer. Its waters are at all times charged with a large amount of suspended silt.

The outflowing water is partly derived from springs issuing from the rocks within the drainage area of the glacier and its snowfields, but mainly from the melting of the glacier-ice.

During the summer months the surface of the ice is melted, the ice-water finding its way into every crack and fissure in the glacier-ice. Much of this water sinks to the bottom of the glacier, where a portion of it soaks into the ground, while the remainder gravitates as small englacial streams towards the river draining the glacier-bed.

The internal heat of the Earth is conducted to the surface in all parts of the globe. This heat comes in contact with the base of the glacier and melts the ice at an estimated average rate of about one-fourth of an inch a year.

The pressure exerted by a moving body, such as a mass of ice, represents the expenditure of mechanical energy which is not lost, but transformed into heat. When the foot-lbs. of energy are known, the equivalent calorific value can easily be determined. The pressure lowers the melting-point of ice, so that in the case of thick sheets the melting-point will be sensibly less than 32° F.

It has been proved experimentally that every atmosphere of pressure (14·7 lbs. per square inch) lowers the melting-point 0·0133° F., which means that a pressure of 1103 lbs. per square inch will lower the melting-point 1° F. Taking the specific gravity of ice at 0·918, we find that to obtain a pressure of 1103 lbs. per square inch we require a sheet of ice 2775 feet thick.[1]

In other words, the melting-point at the base of a glacier 2775 feet thick will be 1° F. less than 32° F.=31° F. And since the pressure is proportional

[1] $\frac{0\cdot0133}{1} \times 14\cdot7 = 1103$ lbs. per sq. in.; S.G. of ice=0·918; weight of a cubic foot of water=62·32 lbs.; therefore pressure of 1 foot of water=0·433 lb. per sq. in., as $\frac{62\cdot32}{144} = 0\cdot433$. Therefore pressure of 1 foot of ice=0·433×0·918=0·397 lb. per sq. in. And 1103 lbs. ÷ 0·397 = 2775 feet of ice for 1° F.

to the depth, it follows that for a thickness of 5550 feet the melting-point will be 2° less=30° F. Therefore, as a near approximation, we may say that for every mile thick of ice the melting-point is lowered 2° F.

Agassiz proved by numerous experiments in a hole sunk to the depth of 200 feet in solid glacier-ice that the temperature at that depth was only 31·93° F. when the surface temperature was at freezing-point. Hence he assumed that in all thick glaciers the temperature of the base of the ice is constantly maintained at melting-point; but the proof of this has still to be demonstrated.

Retreat of Glaciers.—In certain circumstances the rate of retreat of a glacier may be not less rapid than the rate of advance. The Barry glacier in Harriman Fiord, Alaska, retreated 3½ miles between 1899 and 1910; and approximately 600 feet of this retreat took place in the year 1909–1910. Most existing glaciers in both hemispheres are shrinking in size.

The glaciers in Yakutat Bay, Alaska, show clear evidence of three periods of temporary advance during the general recession now in progress. The last advance, in 1906, was short and spasmodic, and has been not unreasonably attributed by Tarr and Martin [1] to the unusual supply of snow and ice shaken down from the mountains by the great Yakutat earthquakes in September 1899. On account of the slow rate of flow, the terminal end of the glaciers did not respond to the new impulse until six years had elapsed, and naturally the shortest glaciers were the first to be affected.

The glacier on Mount Sarmiento, in South America, which descended to the sea when Darwin found it in 1836, is now separated from the shore by a vigorous growth of forest trees. The Jacobshavn glacier, in Greenland, has retreated four miles since 1850; and the East Glacier in Spitzbergen is more than a mile away from its terminal face of 1862.

In Scandinavia the snowline is gradually retreating up the mountains, and the glaciers have withdrawn 3000 feet in a century.

The same tale of shrinking glaciers comes from the Altai and Himalaya Mountains, from New Zealand and Antarctic regions. It probably arises from a gradual decrease of precipitation rather than climatic change.

Fluctuations of Glaciers.—Glaciers may retreat for a time and then advance rapidly. The Sefström glacier, in Spitzbergen, affords a good example of alternating slow retreat and rapid advance. In 1882 [2] this glacier ended well within its own outlet with its sea-front about two miles distant from the waters of the main fiord. When re-examined by Professor De Geer fourteen years later, in 1896, the glacier had made an astonishing advance. It now filled the bottom of its valley right up to the hills and bulged out in a wide lobe into Ekman Bay, thereby obliterating the inlet. The distance covered by the advance was a little over four miles.

In 1908 the glacier had retreated a mile and a half, and by August 1910, there had been further recession.

De Geer [3] considers that the fluctuations are related to the changes in the annual snowfall.

Geological Work of Glaciers.

Glaciers as agents of denudation perform a twofold office. They (1) transport material from a higher to a lower level; and (2) they degrade the land by eroding the bottom and sides of their bed.

[1] R. S. Tarr and Lawrence Martin, "The Earthquakes of Yakutat Bay, Alaska, in Sept. 1899," *Prof. Paper* 69, *U.S. Geo. Survey*, 1912.

[2] G. W. Lamplugh, "On the Shelly Moraine of the Sefström Glacier and other Spitzbergen Phenomena Illustrative of British Glacial Conditions," *Proc. Yorks. Geol. Soc.*, vol. xvii. p. 222.

[3] *Loc. cit.*, p. 221.

Glaciers as Transport Agents.—A valley-glacier may transport material (*a*) on its surface; (*b*) scattered throughout the body of the ice; or (*c*) dragged along the floor.

The surface load may find its way on to the glacier in various ways. Among the higher mountain-chains where glaciers exist the frosts are very severe. The winter frosts break up and shatter the rocks forming the valley-walls. The fragments and masses thus broken may form *talus* deposits that slowly slide down on to the edge of the glacier; or, when assisted by gravity on steep slopes, they may fall on to the ice as soon as they are detached; or they may be carried down by avalanches; or transported from the heights above by the snowfields that feed the glacier at its sources.

The rocky load that lies on the surface of a glacier, or accumulates at the end, may be *lateral*, *medial*, or *terminal*, according to the position it occupies.

The debris that falls on to the sides of the glacier forms marginal belts or *lateral moraines*.

When two glaciers from adjacent valleys unite, their inner lateral moraines come together and form what is called a *medial moraine* (figs. 20, 21).

When more than two glaciers unite, the surface of the trunk glacier may carry several belts of medial moraine, although the position of these will not be quite medial.

FIG. 20.—Medial moraines, Mer-de-Glace.

At the place where the glacier ends, that is the *terminal face*, the surface debris is tipped over and piled up in pell-mell fashion. Where it falls into the glacier-river it is washed away and soon becomes rounded and water-worn.

A large proportion of the rocky surface load falls into the crevasses and thus becomes engulfed in the body of the ice. This, with much of the debris carried down by the tributary snowfields, forms the *englacial* load of the glacier.

The material broken up by the pressure and grinding action of the moving ice, or plucked from the bed and carried forward along the floor of the valley at the base of the glacier, is termed *subglacial*.

On account of the differential rate of flow a constant rearrangement is going on in the body of the glacier, with the result that much of the rocky load carried on the surface at the upper end gradually becomes engulfed in the ice, while many of the subglacial blocks come to the surface.

5

The englacial rocky debris is carried down to the terminal face, where it is piled up with the material tipped from the surface moraines. A large portion of the subglacial debris is washed away by the glacier-river.

The material composing the surface moraines consists mainly of angular blocks of all sizes, ranging up to masses 200 tons or more in weight, mixed with small angular fragments and clay. A few of the blocks show striated surfaces produced by the stones rubbing against one another, or by rubbing against the valley-walls when frozen in the moving ice.

The englacial debris is frequently arranged in layers *lying parallel to the névé* foliation. This foliation is frequently very minute, and is always very striking where layers of clean ice alternate with layers of earthy matter. These dirt layers are frequently inclined at steep angles, the inclination being generally towards the head of the glacier. In some glaciers, particularly near the terminal face, the layers are sharply folded and contorted, due to the differential flow of the upper and lower layers of the ice.

Many glaciers that are quite free from morainic matter in the upper portion

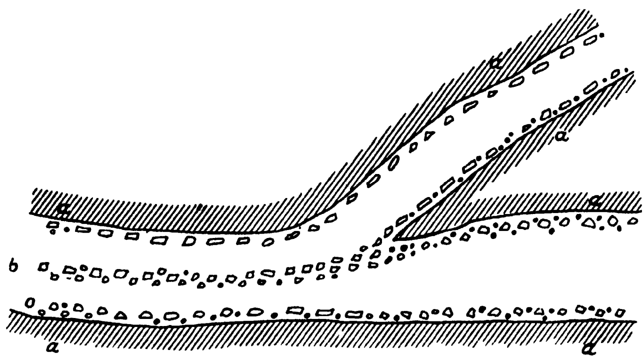


FIG. 21.—Showing lateral and medial moraines.

(*a*) Lateral moraines. (*b*) Medial moraine.

of their course are covered with rocky debris at their lower end. This material, which sometimes appears in patches and sometimes as a continuous sheet across the whole width of the ice, is subglacial and englacial debris that has found its way to the surface partly owing to the culminative effects of long-continued surface ablation, and partly owing to the upward flow of the lower layers of ice due to differential flow and the obstructing apron of debris in front.

There is abundant evidence in Alaska and Spitzbergen that glaciers which have crossed an arm of the sea have picked up marine material from the sea-floor and transported it over the land lying in the path of their advance. It was doubtless in this way that the shelly glacial drifts of North-Western Europe were spread by the ice-sheets of the Glacial Period over the land surrounding the sea-basins.

Similar evidence is obtainable in the Antarctic region. Professor T. W. Edgeworth David [1] states that the Ross-Barrier ice-sheet climbs slopes, and thrusts up marine muds for a vertical distance of 300 feet (formerly 800 feet).

The marine shells scooped up by ice are often in a perfect state of preservation. At first sight this is somewhat puzzling, but is probably due to the shells being lifted bodily in frozen masses of sediment. A. H. Brooks

[1] *Quart. Jour. Geol. Soc.*, No. 278, 1914, p. 230.

reports that in the Klondike the drifts are permanently frozen to a depth of over 300 feet.

Glacier-Drifts (fig. 22).—The water that drains a glacier transports a portion of the angular rubble carried by the ice. The angular rubble soon becomes

FIG. 22.—Section of terminal moraine with indentated glacial drift.

rounded, and when deposited with the fine silt forms what is called a *fluvio-glacial drift*. These drifts accumulate outside the terminal moraines, as shown in fig. 22.

Ground-Moraines.—The broken-up rock and clays that accumulate under a glacier or sheet of ice, as well as all the drift that is deposited beneath the advancing ice, constitutes what is termed *ground-moraine*, *boulder-clay*, or *till*.

The thickness of the ground-moraine is notably irregular. It may vary in a hundred yards from a few feet to many hundreds of feet. The distribution is equally variable, but for the most part subglacial deposits of this kind are principally developed in the lower end of glacial valleys and in depressions among the foothills. Subglacial drifts are sometimes present on ridges and absent in the neighbouring low ground and valleys.

When the boulder-clay occurs in long ridges, as it frequently does in the lower foothills, it forms what in Scotland are called *drums* or *drumlins*, that run in the general direction of the rock-striation or ice-movement.

The *till* of Scotland varies from 0 to 160 feet thick, and that of North America from 0 to 500 feet. In Germany the Pleistocene glacial drift varies from 0 to 670 feet thick. In Greenland there are enormous accumulations of ground-moraine on the edge of the inland ice at Austmannatjern, where there are no *nunataks*, and not a vestige of surface moraine visible.

Nunataks are peaks of rock projecting above the level of an ice-sheet or ice-plateau, and where they are absent it is obvious that no fragments of rock can be shed on to the surface of the ice.

Glaciers as Agents of Erosion.—When a thin sheet of snow lying on a steep mountain slope moves downhill, it heaps the loose shingle and soil on which it rests into small furrows that are not unlike those made by a harrow on cultivated land. This action cannot be described as erosion, since the material is already loose and is merely displaced by the sliding snow. Even a thick snowfield will glide downhill without eroding its bed, except where a boulder is frozen into its base. In this case the boulder will furrow the loose material through which it moves, and scratch projecting rocks that lie in its path.

Large glaciers are capable of wearing away the surface of the rocks forming their bed by the pressure of their mass alone, which amounts to 25·5 tons per square foot for every thousand feet of ice. When the pressure exerted by the ice exceeds the ultimate strength of the rock over which it flows, the crumbling and erosion of the rock-surface must be the inevitable result. It is probable, however, that most of the erosion is effected by the fragments of rock frozen into the base of the ice. As the glacier moves onward, these fragments, being held in the firm grip of the ice, plough into the softer rocks, while they scratch and abrade the harder like a gigantic rasp. In this way a glacier deepens and widens the valley in which it flows.

The maximum thickness of the Greenland ice is estimated to be not less

than 5000 feet, and that of the Antarctic is probably much more. In the Pleistocene the ice is believed to have attained a thickness of 5000 feet in Scotland, 3000 feet in the Alps and Scandinavia, 7000 feet in New Zealand, and 6000 feet in North America. The erosive power of such masses of moving ice must have been enormous (Plate IX)

It is, of course, impossible to watch the progress of the erosive work being carried on by existing glaciers; but if we examine a valley that has been at one time occupied by a glacier, we find that all the irregularities have been worn down, and that the bottom and sides are smooth or gently undulating. Hummocks of rock that lie in the valley-floor are found to be scored and furrowed, while projecting spurs are truncated Where the glaciation has been prolonged and severe, rock-basins are scooped out in the floor of the valley, and in many cases the neighbouring mountain slopes are excavated into benches or platforms

No other natural agent than ice is known that could effect these changes; and when we find at the lower end of the valley huge piles of ancient morainic matter, then are we sure that moving ice was responsible for the work

Country that has been at one time overrun by ice always presents smooth

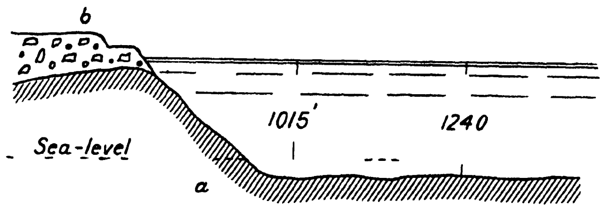


FIG 23 —Section of lower end of Lake Wakatipu rock basin, N Z, an over deepened glaciated valley (see p 73)

(a) Altered greywacke (b) Kingston ancient moraine

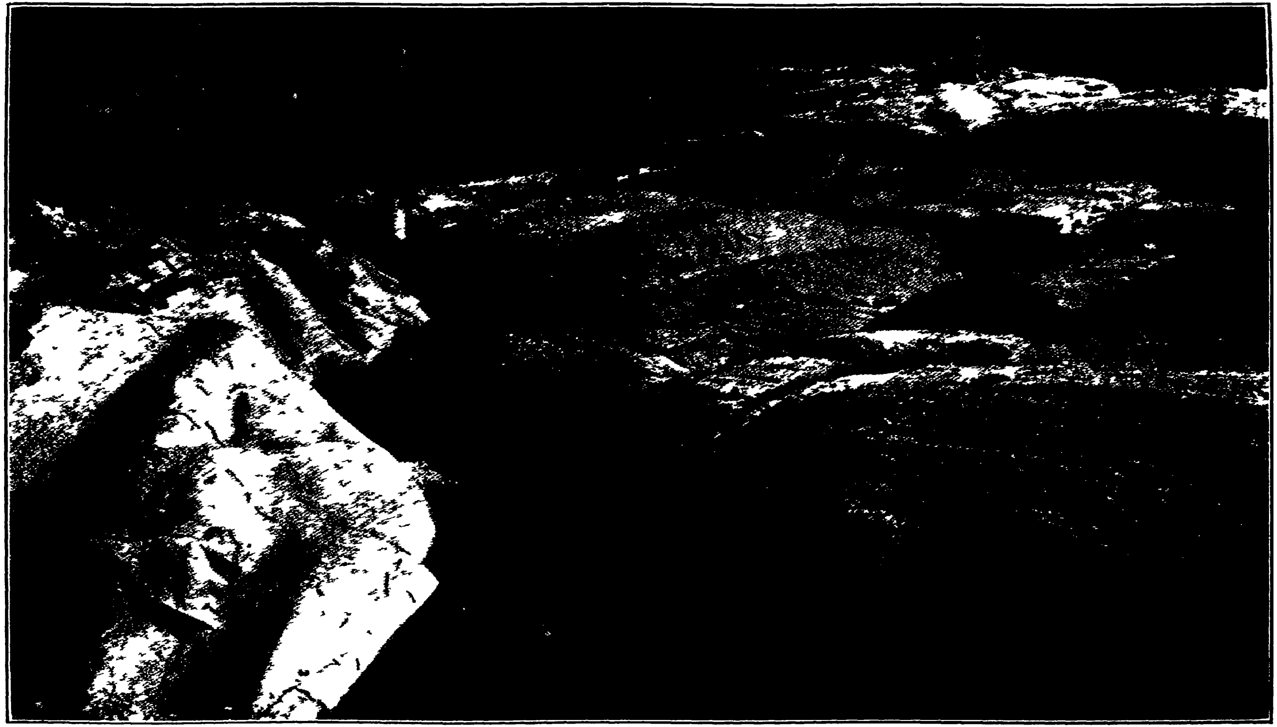
rounded contours and flowing outlines, except among the higher mountains where the recent work of frost has shattered and broken up the ice-worn surfaces The most striking effects of glacial erosion are usually found in the valleys and foothills of recently glaciated countries

All geologists are agreed as to the ability of glaciers to wear away and plane the surfaces over which they flow, but all are not agreed as to the maximum amount of erosion they are capable of performing

Many maintain that the erosive effects of glaciers are small and can never amount to more than the smoothing, scratching, and superficial planing of the rocks over which the ice flows Glaciers, they contend, are incapable of excavating to any extent, but always occupy pre-existing valleys Others are prepared to maintain that glaciers are not only able to excavate valleys but even to *overdeepen* them in certain circumstances

The truth probably lies between these extreme views Recent investigation would tend to show that the present drainage systems in glaciated regions had been already determined at the advent of the *Great Ice Age*, and that the glaciers merely took possession of valleys already in existence These valleys they widened and deepened, and in favourable situations *overdeepened*, so as to form the rock-basins of many of the mountain valley-lakes of the present day.

The enormous amount of *rock-flour* in the form of suspended matter annually



GLACIATED ROCK SURFACES. (U. S. Geol. Survey.)

FIG. 24.—Showing ice striated stone

transported from below a glacier by the glacier-river is satisfactory evidence of the wear and tear that is constantly going on under the moving river of ice.

Glacial Striæ.—Many of the blocks of stone in a ground-moraine are scratched and grooved with parallel *striæ* (fig. 24). Some boulders are striated with two systems of striæ, crossing each other at a more or less acute angle. This may mean that the first position of the block became changed in respect of the line of movement of the ice, thus permitting a second set of striæ to be scored on the face of the stone.

Striated stones, although most common in boulder-clays, are frequently found in the moraines of existing glaciers.

The striæ are best preserved on granite, diorite, quartzite, greywacke, hard sandstones and limestones. Where the glacier flowed over such soft rocks as shale, chalky clays, marls, phyllite, slate, or mica-schist, striated stones are seldom or never met with in the subglacial debris. The striæ formed on basalts and all basic igneous rocks are soon effaced by weathering, as the felspar constituents of these rocks are acted on by atmospheric carbonic acid and moisture with comparative rapidity. Where the striated basaltic boulder has been embedded in impervious clay, the striæ may remain fresh and sharp for a considerable time.

Roches Moutonnées (fig. 25).—These are rounded, hummocky, or whale-backed bosses or ridges of hard rock that have been worn down by an overriding

FIG. 25.—Showing *roches moutonnées*.

stream of ice. They generally occur on the floor of ancient glacial valleys and on valley slopes, but some beautiful examples are found at high altitudes, as, for example, near the summit of Mount Rosa in New Zealand, at a height of 5500 feet above the sea and 3000 feet above the Hooker Glacier.

Erratics.—These are blocks of rock that have been transported by ice some distance from the parent-rock. In some cases they have been carried from one watershed to another, and even from one country to another. The Scandinavian ice-sheet which flowed down the North Sea carried many foreign rocks from the frozen north and left them stranded on the shores and inland parts of England.

Perched Blocks.—Masses of rock that have been left stranded by the retreating ice on the summit of ridges or on the flanks of mountains are termed *perched blocks*. Some perched blocks have been transported many miles from their parent-rock; and in many cases they have been left by the melting ice in prominent or precarious positions, hence the name.

Perched blocks (fig. 26) are angular or partially rounded according to the amount of wear and tear they have suffered during their journey. When carried on the surface or in the body of the ice, they are angular, but when they were frozen into the base of the glacier and dragged along the rocky floor, they were usually smoothed, striated, and sometimes polished on the lower side.

One of the most notable perched blocks in Europe is the *Pierre à Bot*,

a huge block of granite from the Mont Blanc range, stranded about two miles from Neuchâtel. It is estimated to weigh about 3000 tons.

Glacial Benches.—These may be, according to their origin, (*a*) *detrital* or (*b*) *rock-cut*.

FIG. 26.—Perched block, Arran.

Detrital Benches (fig. 27) are formed in parallel lines along the slopes of ancient glacial valleys. Two, three, or as many as twenty or more of these may rise on the mountain side one above another like a flight of gigantic steps. They are not horizontal, but slope at a low angle towards the lower end of the valley.

These detrital terraces are ancient lateral moraines that accumulated along the edge of the glacier. When the glacier shrunk in depth, the rocky belt

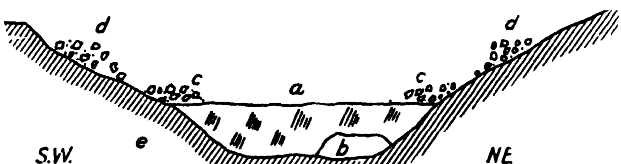
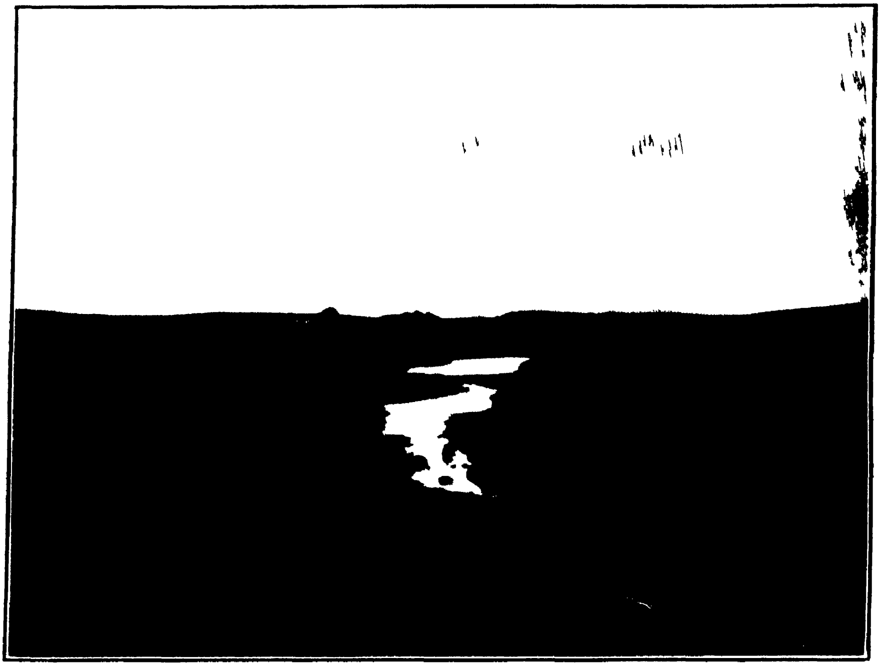


FIG. 27.—Showing rubble terraces now being formed on the edge of the Hooker Glacier, New Zealand.

(*a*) Glacier-ice.
(*b*) Glacier-river.
(*c*) Lateral moraines.
(*d*) Ancient lateral moraines forming rubble terraces.
(*e*) Greywacke and slaty shales.

of detritus was dropped on the mountain slope, and piled up in the form of a rubble platform or bench. At its next resting-place another belt of debris accumulated on the edge of the ice again to be deposited on the flank of the range as the melting ice shrank in depth, thus forming a second bench ; and so on, other benches being formed in the same way so long as the glacier, by fits and starts, continued to shrink in its bed.

Glacial Rock-Terraces have been excavated out of the mountain slope forming the wall of the ancient glacial valley. Two, three, or many of these benches may occur one above the other. They are not so continuous as detrital benches, nor is their inclination so uniform. They are more or less undulating



A. SHOWING DISSECTION OF ALLUVIAL PLAIN.

B. HANGING VALLEY. (After Tarr, U.S. Geol. Survey.)

in longitudinal section, and may vary considerably in width, this variation being due to the irregularities of the original slope in which they were excavated.

Rock-cut terraces are only found in regions that have been subject to intense glacial erosion. A striking example of this kind of ice-erosion is seen on the slopes of Ben More in New Zealand, where more than thirty benches have been carved in the mountain slope between Lake Luna and the summit of the mountain in a height of about 3000 feet.

Spurs that projected into glacial valleys are generally found to have been truncated, and where the ice flowed over them their crest is in most cases planed down into a platform as shown in fig. 28.

Crag and Tail.—Ice-worn ridges usually present a long continuous slope in the direction from which the ice travelled, and a steep slope on the lee or further end where frequently a certain amount of rocky debris collected. This form of ice-erosion is known as the *crag and tail*, and is well seen in fig. 25.

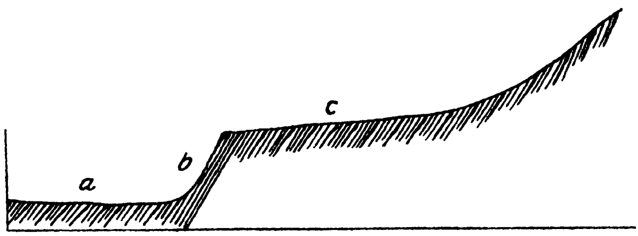


FIG. 28.—Showing truncation and planing of projecting spur.
(*a*) Floor of glacial valley. (*b*) Truncated end of spur.
(*c*) Crest of spur planed into a platform.

Fluvio-Glacial Work of Glaciers.—In another place we have seen that every valley-glacier is drained by a river which issues from an ice-tunnel at the end of the glacier. Glacier-rivers always carry a certain amount of suspended matter in the form of silt or rock-flour ; and in the case of many ice-fed streams the amount of fine silt thus carried in suspension is so large that their waters possess a milky-white colour.

Besides rock-flour the river also transports sand and gravel derived from the bottom of the glacier. The coarser material, frequently mingled with angular morainic debris, is dropped first, further on the finer gravels, and lastly the sand and silt. In this way glacier-streams frequently build up alluvial plains called glacier *valley-trains.*

A *valley-train* (fig. 29) is thus a continuous sheet of *glacial drift*, graduating from the purely morainic drift at the head to the purely fluviatile deposit at the end. The material is always more or less stratified throughout, and in all of it, both coarse and fine, the angular blocks as well as the water-worn gravels have a common glacial origin.

Where the glacial river discharges its load into a lake or a bay, a delta is formed. In this way many valley-lakes have been filled, or partially filled, and large areas reclaimed from the sea.

When the outlet of a glacier-river has become blocked with some obstruction, such as an ice-fall or an accumulation of morainic debris, the flow of the river is checked, with the result that the transported load of sand and gravel can no longer be carried forward to the valley-train, but is deposited in the ice-tunnels of the subglacial streams. When the glacier retreats, these deposits of sand and gravel remain in the form of ridges that occupy the sites of the

subglacial streams, their form, length, and height being determined by the form and size of the ice-tunnels which they filled.

Deposits of this kind frequently run parallel with the valley-walls. They are common in all recently glaciated regions. In the Central Plain of Ireland they are called *eskers,* and in Scotland *kames.* The sand and gravel of eskers are usually sorted into layers of coarse and fine material, and in this respect they cannot be distinguished from ordinary *river-drifts.*

At the time the confluent glaciers deployed from the alpine valleys and still occupied the low country and plains, numerous streams would doubtless issue from the melting front of the ice.

The ice-sheet would override the land, and its flow would be towards the sea independently of the minor irregularities of the contours. Hence the escaping waters would at first flow with little relation to the existing drainage

FIG. 29.—Valley-train below Hidden Glacier, Alaska (After Gilbert, U.S Geo. Survey)

lines. Streams would be discharged over hills and ridges as well as over the plains, walls of ice forming the enclosing barriers of the channels. Wherever they went these streams would leave a trail of well-worn glacial drift in the form of sand and gravel, with perhaps here and there a sporadic mass of rock dropped from the base of the melting ice.

It was probably in this way that the sheets of *plateau-gravels* of South Germany, Alaska, and New Zealand were formed. These high-level gravels are spread over plateaux, hills, ridges, and mountain slopes frequently without any relation to the present topography. In many places they fill up inland alpine valleys.

According to their situation they may merge into or overlie *boulder-clay,* morainic debris, marine sands, and raised-beach gravels.

These drifts are most striking when they form mounds which run across valleys and plains, or even over watersheds. Such mounds when found on plains or along hillsides constitute the eskers described above.

Topographical Effects of Glaciers.—A glacier or ice-sheet modifies the topography of the land over which it moves by its destructive effect as an agent of erosion, but its constructive effect as an agent of transport is not insignificant.

A valley-glacier in an alpine region deepens and widens the valley which

it occupies. The extent to which the glacier is able to modify the original topographical features is dependent on the hardness of the country rock, the depth of the ice, the rate of flow, and the duration of the glaciation.

The cross-section of valleys that owe their existence to stream erosion is usually V-shaped; and the sides are usually irregular. Glacier erosion usually changes the V-shaped form into a U-shaped one.

Where the valley traverses granite, gneiss, or other hard rock, its sides are frequently carved into approximately vertical walls; but in softer rocks the form assumed is commonly that of a U with its sides spread out in a gentle catenary curve.

Where the trunk glacier has deepened its bed more rapidly than the lateral tributary ice-streams, the valley-floor of the tributary streams is found to occupy a higher level than that of the trunk valley. Such *hanging valleys*, as they are called, are common in all recently glaciated regions. Many fine examples of *hanging valleys* are seen in the fiordland of Otago, Norway, Alaska, and other parts of North America, and elsewhere (Plate X., B).

The descent from the end of the *hanging valley* is frequently quite abrupt,

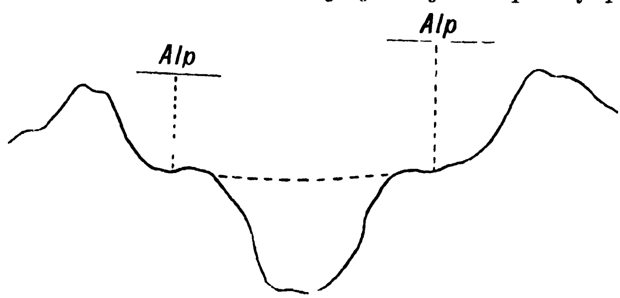


FIG. 29A.—Showing alps or mountain meadows.

with the result that the drainage of the lateral valley is compelled to find its way to the main valley in the form of a waterfall or cascade.

In fiordlands and in recently glaciated mountains composed of hard crystalline rocks, the cross-section of the valleys frequently shows two phases of formation—namely, a wide upper flat-bottomed valley and a lower narrow U-shaped valley excavated in the floor of the upper one. The portions of the floor of the upper valley that have escaped denudation form the terraces or mountain meadows known in Switzerland as *alp* (fig. 29A). Small rock-cut basins or *tarns* are common features of these high mountain meadows.

We have already seen that the effect of moving ice is to wear away all the corners and minor irregularities of the landscape. The result of this planing down of the surface features is that a region recently overrun by an ice-sheet usually presents smooth flowing contours and a monotonous sameness of outline, dome-shaped hills, whale-backed ridges, and mammillated slopes everywhere meeting the eye.

The walls of glaciated valleys are usually even, being free from projecting spurs and ridges; but where spurs do project into the valley they are usually truncated, and their crests planed down into terrace-like platforms.

All the recently glaciated valleys in New Zealand and many in Switzerland and Alaska have been *overdeepened* by the ice. The depressions thus formed are now lake-basins. The size and depth of many of these basins have been increased by barriers of morainic debris deposited at their lower end (fig. 23).

The head of glaciated valleys is frequently found to open out into a circular basin known as a *cirque*, on the floor of which there may be one or more shallow *corrie-lakes* (fig. 30) or lagoons occupying rock-cut basins. According to Professor Bonney's view, cirques occupy pre-glacial hollows cut by convergent streams with walls modified by ice erosion. Richter, on the other hand, maintains that they are the result of frost-shattering above the level of the ice. The frost dislodges masses of rock, which fall on to the ice and are carried away, whereby the formation of a talus is prevented. The ice protects the floor of the cirque, which is thus relatively flat, while the absence of a protecting apron or talus permits the frost to sap and wear away the walls till they become steep or even vertical.

Where two glacial valleys on opposite sides of a mountain-chain head together, as they so frequently do where the original valleys follow some powerful fault or line of structural weakness, the cutting back of the cirques may result in the removal of the dividing ridge, and in its place we may find a plateau or flat saddle occupied by swamps or shallow lagoons.

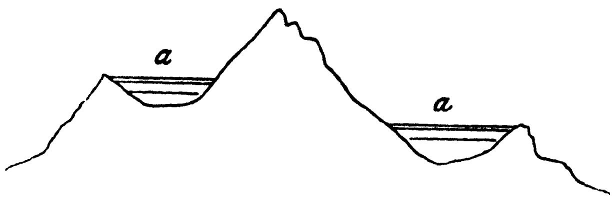


FIG. 30.—Showing cross-section of two cirques on opposite sides of a range.
(*a*) Corrie-lakes.

Where one cirque lies at a lower level than the other, the lower by its recession is able to pirate the drainage of the higher, which is thus reversed or carried to the other watershed. Examples of *reversed drainage* are not uncommon in alpine New Zealand and Alaska. Much of the stream-pirating and beheading described in a preceding page has been doubtless accelerated, if not initiated, by ice-erosion.

Sharp-peaked mountains with excessively steep walls are frequently found in glaciated regions on the margins of ice-caps. Many good examples of these remarkable peaks, which are called *tinds*, have been developed on the margin of the Norwegian plateau glaciers. Mitre Peak in the fiordland of Otago is a typical example of a tind. Tinds have been obviously exposed to intense ice-erosion, and the conical shape which they frequently assume may not improbably be due to the shattering and exfoliation of successive layers of rock by frost action since the retreat of the ice-sheet.

The terminal debris of glaciers is frequently piled up in the form of hills and mounds disposed in crescent shape on the plains where the glacier deployed from its alpine valley, and although these morainic hills seldom exceed a height of 300 feet, they are nearly always a striking feature in the landscape, as they present a curious assemblage of hills and undrained hollows of the *knob-and-basin* type.

Crescent-shaped morainic mounds, one behind another, may be traced up an alpine valley, each mound marking a place where the glacier rested for a time during its final retreat. The highest mounds, being the last formed, are always the freshest.

The valley-glaciers of Alaska, Alps, Pyrenees, Himalayas, and New Zealand are but the remnants or stumps of great ice-streams that, during the Great Ice

Age, descended from the mountains and spread over the neighbouring foothills and plains.

The freshness of some of the glaciated slopes and esker-mounds of sand and gravel in Scotland, Alaska, and New Zealand is often remarkable. In many places the contours look so smooth and fresh that one is tempted to think they were moulded but yesterday, or that the forces of denudation must have been held in abeyance since the close of the Glacial Period. This freshness is all the more striking when we observe that contiguous areas occupied by hard rock have been deeply dissected by streams. This differential erosion is a common feature of all glaciated regions.

The preservation of the glaciated forms and mounds of morainic debris is believed to have been due to the protection afforded by permanent snow-fields. It is contended that during and for some time after the recession of the ice, the refrigeration would still be sufficient to allow the formation of sheets of permanent or nearly permanent snow that would protect the ground on which they lay from subaerial waste or denudation, stream erosion being confined to the water-courses and lines of drainage.

The evidences of recent glaciation in the form of boulder-clays, moraines, and erratics are not always conspicuous even in regions that have been subjected to intense ice-erosion. In Alaska during the maximum glaciation the chief work of the ice was ground erosion with off-shore deposition of detritus; and, as in all intensely glaciated regions, the glacial deposits above sea-level are thin and scattered, and were mostly deposited during the ice retreat.

Glacial Lakes.—Ice-dammed lakes exist on the margin of the Frederikshaab ice-apron on the fringe of the Greenland ice-cap. One of these, the Tasersuak, 12 miles long and over 2 wide, stands at a height of 940 feet above the sea and is blocked by ice at both ends. It drains through a canal to a smaller lake at a height of 640 feet.

A glacier descending a steep tributary valley may by a sudden advance impound the drainage of the main valley and form a lake. Such a lake is necessarily short-lived, since the ice-barrier is soon destroyed. A remarkable case is that of the tributary glacier which blocked the Suru Valley in the Himalayas in 1896, and held up the drainage till a lake over 20 miles long was formed. When the ice-barrier was broken through, the valley below was devastated for a distance of 40 miles.

More important is the case where the drainage of a tributary valley is held up by the glacier occupying the main valley. If the ice-barrier stands above the level of the pass or *col* at the head of the tributary valley, the drainage of the lake may be reversed, and the height of the col will represent the highest level to which the lake can rise. A typical example of a lake of this class is the well-known Marjelen See at the elbow of the great Aletsch glacier in the Alps. This glacier-lake is impounded in a tributary valley, and at one time drained over a low col into the adjoining valley occupied by the Fiescher glacier. Such a lake, it is thought by some writers, might in time give rise to a detrital beach at the level of the col.

Ice-dammed lakes possess a peculiar interest in that they are believed by some writers to offer a satisfactory explanation of the origin of certain step-like detrital terraces that are a conspicuous picture in many recently glaciated regions. It was first suggested by Agassiz, and afterwards urged by Jamieson,[1] that the famous Parallel Roads of Glenroy, in Argyllshire, are the beaches of freshwater lakes that seem to have arisen from glaciers damming the mouths of the valleys and reversing the drainage. According to this view, each of the

[1] *Quart. Jour. Geol. Soc.*, vol. xix. pp. 235–259, 1863.

three terraces marks a temporary level of the ancient Glenroy lake. The terraces are perfectly horizontal, contour around the valley-walls, and occur at a height of 847 feet, 1059 feet, and 1140 feet above sea-level respectively.

The existence of ice-dammed lakes has been clearly demonstrated in New Zealand, North England, Scotland, North America (*e.g.* the glacial lake Agassiz), and other intensely glaciated regions; but there is grave doubt as to the ability of such glacier-lakes to explain the genesis of many of the remarkable tiers of glacial terraces that are such a prominent feature in the topography of Alpine New Zealand. Take a typical case. On the east side of the coastal range the walls of the main valley leading up to Burke's Pass are terraced nearly up to the crest, the remains of about forty benches being clearly discernible.[1] The valley opens on to the foothills at the back of the Canterbury Plains, and it is almost inconceivable that there ever existed in these low foothills a mass of ice of sufficient magnitude to form a barrier across the main valley and impound a glacier-lake at a height of 4000 feet above the sea. It seems easier to suppose that the terraces represent the lines of frost-shattered debris that collected on the edge of the valley ice in the form of lateral talus-like aprons. Beautiful terraces of this kind have been recently formed by the Hooker glacier near Mount Cook. They contour round the valley-walls at different levels, and consist of angular rock-debris mingled with waterworn sands and gravel brought down by the small rivulets that drain the adjoining slopes. The Hooker glacier has been subject to alternating periods of rapid shrinkage and comparative rest. The lateral fringing terraces were obviously formed during the intervals of rest. A well-marked terrace has already accumulated at the present surface-level of the glacier. This glacier, it should be noted, is little more than the shrunken skeleton of the great ice-river that at one time filled the valley; and it illustrates, in a striking manner, that fact that a considerable retreat of the terminal face of a glacier is always accompanied by a corresponding shrinkage in depth. In other words, terminal ablation and surface ablation are contemporaneous and co-relative.

Most of the alpine lakes of Italy and Switzerland are partly ice-eroded and partly dammed by morainic matter. The bottom of some of them lies below sea-level.

SUMMARY.

(1) Snow (*a*) protects the land on which it rests from the influence of frost, rain, and other subaerial agents of denudation; and (*b*) it has a destructive effect when it falls or slides down steep slopes by carrying loose rocks from a higher to a lower level.

(2) Glaciers are found in the polar regions and in the higher alpine regions of temperate and warm latitudes. They flow like pitch or asphalt.

(3) Glaciers and ice-sheets are both *destructive* and *constructive*. They wear away the rocks over which they flow by their sheer weight, while the boulders frozen into their base plough into the rock-bed, which thus becomes scored and furrowed and in time deeply eroded or removed.

(4) Glaciers that are overlooked by mountains always carry a load of rocky debris partly on their surface, partly englacial, and partly subglacial.

(5) The debris on the surface of a glacier is arranged in belts running parallel with the sides, forming *lateral* moraines.

(6) Where the glaciers unite, their adjacent lateral moraines form a *medial* moraine.

[1] J. Park, *The Geology of New Zealand*, p. 237, London, 1910.

(7) The transported load when piled at the end of the glacier constitutes what is called a *terminal* moraine.

(8) The broken-up rock and clay that remain on the floor of a glacial valley after the ice has disappeared form what is called a *ground* or *bottom* moraine, *boulder-clay*, or *till*.

(9) When the boulder-clay is piled up in ridges, that run parallel with the hillsides, it forms what are known as *drums* or *drumlins*.

(10) Many of the boulders found in ground-moraines are scored and striated, as also are hard bosses of rock that were overridden by the ice. Such ice-shorn bosses are called *roches moutonnées*.

(11) Large blocks of rock left by the melting ice in conspicuous places are called *perched blocks*, and blocks transported far from the parent-rock are called *erratics*.

(12) Glaciers are drained by rivers which issue from ice-tunnels at the terminal end.

(13) Glacier-rivers carry a load of gravel, sand, and silt, which is spread out as a *valley-train* or deposited in a lake or sea.

(14) The contours of recently glaciated regions are smooth and undulating, all the irregularities and corners having been worn down. The V-shaped form of stream-valleys has been changed to a U-shaped form.

(15) Among the higher chains, the evidences of Pleistocene glaciation have in many places been obliterated by the action of frost, snow, and the erosion of streams. In other places only patches of the rounded and smooth ice-worn surfaces remain.

CHAPTER VI.

THE GEOLOGICAL WORK OF THE SEA.

THE sea covers about three-fourths of the surface of the globe. It is the destination to which most streams and rivers hasten, and the repository into which they discharge the detrital load borne by their waters. The sea ramifies everywhere throughout the globe, and therefore exercises an equalising influence on climate. It is the ultimate source of all streams, which, without it, have no separate existence. It must therefore rank as the greatest of all geological agents.

Composition and Volume.—A thousand parts of sea-water contain 34·40 parts of mineral matter in solution, of which common salt (sodium chloride) comprises about 78 per cent., magnesium chloride nearly 11 per cent., magnesium sulphate 4·7 per cent., sulphate of lime and potassium together 6 per cent.

Sonstadt has shown that sea-water contains over half a grain of gold per ton; and nearly all the common metals and many of the rarer have been detected in it. Oxygen, nitrogen, and carbonic acid are also present in considerable quantity, the amount of carbonic acid being about eighteen times as great as in the atmosphere.

Murray has estimated that the mean depth of the ocean is 12,456 feet, and that the total amount of sea-water is fifteen times the volume of the dry land above the sea. The mineral matter in solution would, he estimates, if precipitated cover the floor of the ocean to a depth of about 175 feet.

The total river discharge into the sea is estimated at 6524 cubic miles per year, carrying half a cubic mile of mineral matter. At this rate it would take the streams 9,000,000 years to add to the sea an amount of mineral matter equal to what it now contains, figures which contain a useful suggestion as to the age of the ocean.

WORK OF THE SEA.

The sea as a geological agent (*a*) *erodes* and *wears away* the dry land; (*b*) *sorts* and *spreads out* the material poured into it by streams and rivers, as well as the products derived from its own erosive work; and (*c*) by its currents *transports* material from one place to another. In other words, the sea is (1) *destructive* and (2) *constructive*.

THE SEA AS A DESTRUCTIVE AGENT.

Erosive Effects of the Sea.—This is (*a*) *chemical* and (*b*) *mechanical*.

Chemical Effects.—The extent of the chemical effects of the sea have not yet been investigated to any extent. It is, however, well known that solutions of salt (sodium chloride) exercise a corrosive effect on many rock-forming

minerals. Besides, sea-water, as stated above, contains a considerable amount of free carbonic acid, the corrosive and disintegrating effect of which on the felspar minerals of rocks or limestones and calcareous aggregates of all kinds cannot be less than that of the atmospheric carbonic acid on the same kind of rock when forming dry land. The chemical erosion of the sea, although no

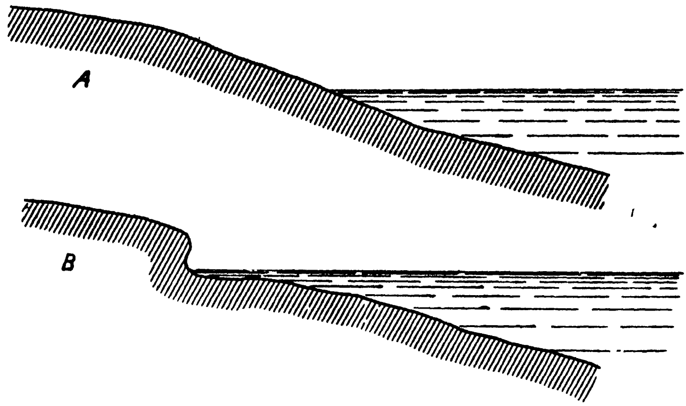


FIG. 31.—Coastal erosion.

(*A*) Showing form of shore before erosion.
(*B*) Showing sea-cliff after erosion.

more measurable to the eye than the gradual and silent waste of an undulating upland, must be considerable in the course of the centuries, and by its softening and disintegrating action cannot fail to be a powerful ally to the more active and apparent forces of mechanical erosion.

Everyone must have observed how prone to decomposition and surface

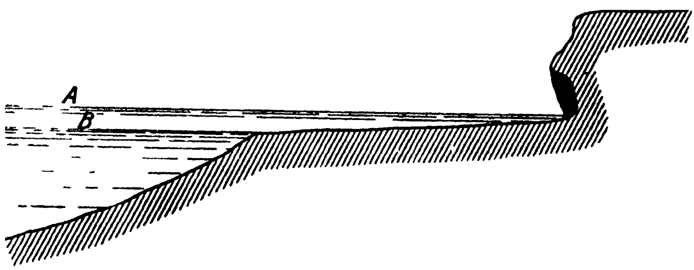


FIG. 32.—Showing marine erosion of sloping bench in Auckland Harbour, N.Z.

(*A*) High-water mark. (*B*) Low-water mark.

weathering are the rocks exposed in cliffs facing the sea. This may be in part due to the briny spray which is carried over the land by the wind coming off the sea, and in part the work of the powerful and active oxidiser ozone which is more abundant on the sea-shore than elsewhere.

Mechanical Effects.—The most obvious effect of the sea is seen in the cutting back of the land so as to form steep faces and cliffs (fig. 31).

The rate of cutting back or recession of the land will depend on the hardness of the rock, its composition, presence or absence of joints, stratification or cleavage planes. Where the rock consists of alternating hard and soft beds,

the soft beds will be cut back more rapidly than the hard, thus leaving an overhanging cornice of hard rock (fig. 34). Even the hardest rocks possess relatively little transverse strength ; consequently the overhanging ledge soon breaks off owing to the stress of its own weight.

The masses of broken rock fall to the foot of the cliff, where they act as a protecting apron by breaking up and in part destroying the erosive effect of the advancing waves. But in time the fallen blocks become pounded up and removed, and once more the active undermining of the sea-cliffs begins.

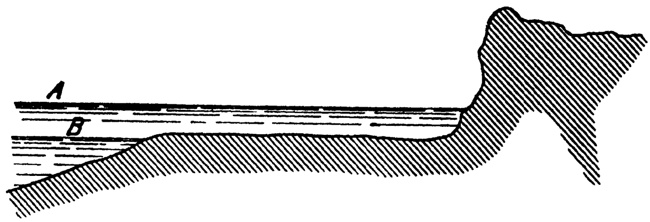


FIG. 33.—Showing flat bench excavated in chalky marls. Amuri Bluff, N.Z.

(*A*) High-water mark. (*B*) Low-water mark.

The manner in which marine erosion is effected varies with the mood of the sea. In its normal mood, which is the tranquil or semi-tranquil, the sea by the constant rise and fall of the tide alternately covers and uncovers a marginal strip of land that in time becomes worn down into a bench that slopes from *low-water* to *high-water mark* (fig. 32). Where the rocks are soft, the bench may be worn into a flat platform lying a foot or two above low-water mark (fig. 33).

During, and for some time after a heavy gale, the sea flings itself furiously against the shore, and in this mood it is very destructive. Pinnacles of rock that have been undermined or loosened by the thundering blows of previous storms are toppled over, while the overhanging portions of cliffs are torn off and the debris spread along the strand, where it is slowly broken up and rounded by the unceasing wave-action of the advancing and retreating tides.

FIG. 34.—Showing coastal erosion.

(*a*) Hard rock. (*b*) Soft rock.
(*c*) Broken rock. (*d*) Waves.

Masses of rock that in normal times lie undisturbed at the foot of the cliffs, during great storms are picked up by the advancing waves and hurled against one another with terrific force. Or where the shore is unprotected by an apron of broken rock, the masses are employed by the waves as battering-rams for bombarding the foot of the cliffs, which thus in time become shattered and finally undermined. When the undermined overhanging portion of the cliff breaks off under the force of gravity, the tumbled rock provides fresh ammunition for another bombardment (fig. 34).

Wave and Tidal Effects.—The constant movement of the sea gradually eats away the edge of the land, and, obviously, if the process were continued long enough, first the islands and then the continents would be shorn down to an almost even plain not much below sea-level. As a matter of fact, many

flat reefs that are just awash at low-water are all that now remain of what were at one time islands standing near the mainland. But the power of the waves does not end here. The angular blocks that are broken off the cliffs are acted on by the tidal movements of the sea as well as by the larger waves of fierce storms, and in time become worn down and rounded. The sharp angular blocks lie along the foot of the cliffs. In the tide-way the blocks are somewhat rounded and smaller. Further out the blocks get smaller and smaller, and more and more rounded, till they eventually pass into *shingle* or beach-gravels. Still further out the shingle becomes smaller and smaller, and finally graduates into sand.

The push and drag of the tides rolls the shingle over and over, and by this everlasting attrition and grinding, the pebbles become more and more rounded, and consequently smaller and smaller, until eventually they are reduced to sand. In the same way the swish of the waves causes a similar abrasion and grinding of the sands, which in time are reduced to a fine silt which is caught up by currents and spread far and near over the floor of the sea. The place of the ground-up shingle and sand is constantly replenished by fresh material broken from the cliffs, which are continually crumbling away under the combined attack of subaerial and marine erosion.

Erosive Effect of Compressed Air.—When the advancing waves fling themselves against a fissured cliff, or one containing fissure-like cavities such as are

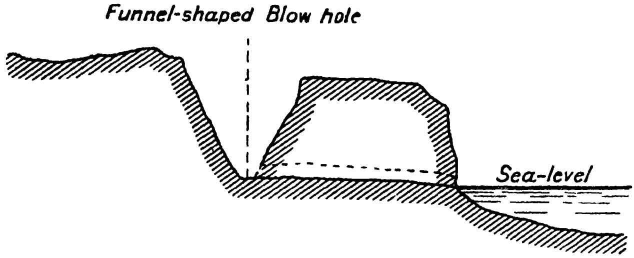


Fig. 35.—Showing funnel-shaped blow-hole, Puketeraki, N.Z.

frequently formed along joint planes or the stratification lines of inclined strata of different degrees of hardness, the contained air is compressed by a pressure equal to the force exerted by the falling wave. When the wave suddenly retreats, the air expands with shattering force, and in this way the cracks and fissures are enlarged and fresh ones opened.

In some places the fissures communicate with the upper surface of the cliff, forming what are known as *blow-holes*, from which air and spray or even a column of water may be projected with great force when the waves dash on the cliffs below. As time goes on, the blow-hole becomes larger and larger, until at last a cavern with a wide funnel-shaped opening on the top of the cliff is formed (fig. 35).

Erosive Effects of Floating Ice.—In the high latitudes of both hemispheres where the seas, lakes, and rivers become frozen over in winter, the effects of ice-erosion are sometimes very striking.

In spring when the river-ice breaks up, it is frequently piled up in narrow gorges till a block takes place. When the impounded waters eventually break away, the sharp-edged sheets of ice scrape and fret against the banks, which in time become undermined and ultimately break away in long strips. Where the course of the river runs through alluvial flats the ice is particularly destructive.

When the ice breaks up in lakes, the floating masses move towards the outlet, where they sometimes accumulate till a "jam" takes place. The force exerted by ice piled up in this way is enormous. Logs of wood entangled in the "jam" are frequently broken into splinters, while all the rocks within the reach of the ice are scored and carved into ledges, or shattered and tumbled over. This erosive effect is seen in most Arctic gulfs and narrow seas.

Floating bergs moving past headlands and along contracted passages chafe and grind against the shores, whereby they may in time excavate narrow benches in the solid rock. Some of the raised benches that contour around the fiords of Norway are believed by some writers to have been formed in this way.

Morphology and Origin of Coastal Topography.—The agents concerned in the sculpturing of coastal topographical features are the sea and subaerial denudation. The forms assumed by the land are determined by the character and arrangement of the rocks, climatic conditions, the contours of the land along the sea littoral, and the direction of the land-movement.

Marine erosion by persistent cliff-cutting causes a steady recession of the shore-line, its activity being mainly directed against the softer rocks which are worn into inlets and bays, while the harder rocks are left as reefs, islands, peninsulas, and projecting headlands.

Coastal plains composed of river deposits, or of soft marine strata of Tertiary age, are usually worn into even or gently curving coasts. Massives of hard rock that offer a uniform resistance to wave-action are often worn into long stretches of sea-cliff unbroken save by minor irregularities.

The greatest diversity of form is found where the land possesses a moderate or high-relief, and is composed of folded strata of varying degrees of hardness. The direction of the folding relatively to the trend of the coast determines the type of coastal topography, always bearing in mind that the direction of the folding may have originally determined the trend of the coast.

If the rocks consist of alternating groups of hard and soft strata folded or tilted parallel with the general trend of the coast, the softer strata will be worn into valleys, and the harder into ridges running more or less parallel with the coast. If subsidence takes place the sea will invade the coastal valleys, and in consequence of this the seaward ridges will become peninsulas. In time the wear and tear of subaerial denudation and sea-erosion may dissect the peninsulas into a chain of long narrow islands fringing the coast. The coasts of North-East Queensland, Southern Chile, and Dalmatia are typical of this type of drowned valleys.

If the rocks are of different degrees of hardness and folded athwart the trend of the coast, we will get a coast-line dissected by numerous valleys, running at right angles to the general trend of the mainland, and separated by ridges running down to the sea. The ends of the ridges are often dissected into islands and reefs that run seaward from the land.

If the coastal terrain is occupied by a complex of mountain-chains the valleys will be deep and narrow, and the ridges steep-sided and crowned with inaccessible peaks. A surface morphology of this kind betokens a region still in the immature stage of erosion.

If subsidence takes place in this deeply dissected region, arms of the sea will invade the valleys, forming fiords or sounds, and deltas will accumulate where the valley streams enter the arms.

If the dissected region, postulated above, be invaded by glaciers, the valley-walls and floor will be modified by ice-erosion ; and if the ice be deep enough to overflow the valley-walls, the crests of the dividing ridges will be shorn into

SEA CLIFF OF TURNER GLACIER, ALASKA (After Tarr, U.S. Geol. Survey.)

smooth flat-crested forms as typically developed in the fiordlands of Otago and Norway.

Geologists are still divided as to the genesis of the Dalmatian and Norwegian types of coastal topography. The older school considers that all coastal irregularities are the work of persistent marine erosion acting on the edge of the land that has remained at the same level for a long period of time. The newer school, led by some American writers of note, goes to the other extreme and postulates that all coastal irregularities are the result of subsidence whereby the sea has been enabled to submerge valleys and contour around land features already sculptured by subaerial denudation.

The supporters of sea-erosion contend that in a coastal terrain composed of rocks of different degrees of hardness, marine erosion, if given sufficient time, will inevitably wear away the coast into inlets, bays, and promontories, and that by a continuance of the erosion the promontories will become broken into islands. As the indentations deepen new promontories are formed, to be afterwards dissected into islands and reefs. In this way it is contended the recession of the land may continue till the first formed islands become worn down to the level of the general plain of marine erosion.

The weakness of this view lies in the certainty that if the land were stationary the erosive power of the sea would be gradually diminished by the accumulation of detritus till it eventually reached zero. If the conditions of ordinary pluvial conditions existed, the products of river-erosion would be spread along the coast and tend to accelerate the decadence of the sea-erosion. It is, however, improbable that sea-erosion could ever reach the vanishing point. It is now recognised, in agreement with the hypothesis of isostasy, that the transference of the load from the land to the sea-floor would bring about the subsidence postulated by the newer school of physiographers.

According to the views of the new school, if a coastal terrain were deeply dissected by pluvial erosion, and subsidence were to take place so as to submerge the valleys to a depth of several hundred feet, we should get a form of coastal topography not unlike that on the west coast of Scotland. If the terrain were a mountain region gashed with deep valleys and gorges, but with an even coastline, we should obtain the topography of a typical fiordland.

In many fiords the mouth is shallower than some portion inside, and the inside depth is not related to the depth of the outer sea, this probably arising from glacial erosion.

On a coast bounded by high land, the sea-floor is correspondingly steep; and in this case the festoon of islands that usually fringes a land of moderate relief is absent.

Generally we may conclude that coastal topography is the result of contemporaneous sea-erosion and river-erosion followed by subsidence in consequence of which the coastal valleys become submerged.

Rate of Marine Erosion.—In bays and in parts of the coast sheltered by headlands, where wave-action is feeble, the recession of the land is mainly the result of cliff-weathering. As the crumbling material falls it is removed by the waves.

The united action of cliff-crumbling and wave-transport in course of time forms a rock-platform that as a rule slopes gently seaward from a little below high-water mark. Rock-platforms of marine-erosion may be narrow, or many hundreds of yards wide, and they may be formed in soft rocks, or in the hardest granite. They are a common coastal feature in all sheltered bays and gulfs. They also occur on the open coast, on the sheltered side of projecting headlands, and on the lee-side of islands.

In sheltered bays, if the cliffs are composed of limestone, calcareous sandstone or shale, the foot of the cliffs may be deeply undercut or sapped by the chemical corrosion of the sea-water.

The recession of the coast by cliff-cutting is greatest on exposed coasts and headlands. If the rocks are stratified and dip towards the sea, the undercutting action of the waves may cause the recession to be relatively rapid. Marine erosion attains its greatest activity on a sinking coast, and as a rule sea-encroachment is an evidence of subsidence.

The rate of coastal recession will depend mainly on the character and arrangement of the rocks and position of the coast, in respect of ocean currents and prevailing winds.

Matthews states that the coasts of Suffolk and Norfolk are being worn away at rates varying from 10 to 45 feet a year. The rate for the Welsh coast, between Llanelly and Kidwelly on the Bristol Channel, is nearly 6 feet a year.[1] These rates are probably greatly in excess of the mean rate of erosion on most coasts.

Effects of Coastal Recession on River Grading.—The cutting back of the coast-line shortens the length of the streams and rivers that drain into the sea. The obvious effect of this recession and shortening is to give the rivers

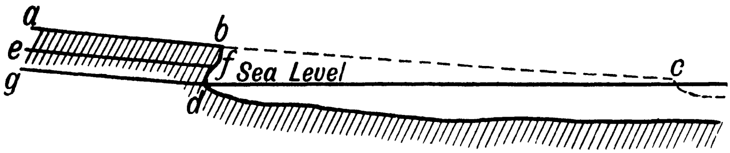


FIG. 36.—Showing effects of coastal recession on river regrading.

a greater velocity on account of the steeper gradient. The greater velocity enables a stream or river to regrade and cut down its bed.

The effects of coastal recession are always most marked where the river flows over an alluvial plain before entering the sea. The river in this situation is enabled, in the process of cutting down its bed to its base-level—the sea, to excavate terraces in the lower part of its course. The effect of coastal recession as regards terrace formation is, therefore, the same as an elevation of the land.

The Canterbury Plains in New Zealand are composed of gravel-drift carried down from the alpine ranges by a number of large rivers. They extend along the coast for over a hundred miles; and north of Timaru, where the coast is swept by a strong northerly current, they have been cut back till they present sea-cliffs, varying from 10 to 50 feet high, the highest cliffs being found where the recession is greatest. The old plane, along which the rivers flowed before the cutting back of the coast-line, is indicated by the line *a b c* (fig. 36), the former point of discharge being at *c*. By the wearing away of the land the point of discharge is now at *d*, and *b d* shows the height of the present sea-cliff. The present plane of flow is along *g d*. During the process of cutting down their beds, the rivers have excavated a series of terraces as indicated by the broken line *e f*. The old flood-level *a b* now forms the highest terrace.

Plain of Marine Denudation.—In a preceding chapter we found that the general effect of all the processes of subaerial denudation was to wear down the dry land to a base-level or peneplain; and similarly we find that the final effect of all the processes of marine erosion is the slicing away of the edge of

[1] F. R. Matthews, *Coast Erosion and Protection*, London, 1913, pp. 11, 21, 22.

the land to a horizontal or gently sloping platform to which the name *plain of marine denudation* is applied. The existence of this marine shelf is proved by the soundings around the coast-line. It is found that nearly all the continents and larger islands are surrounded by a marine shelf.

The shelf slopes gently seawards, and when its edge is reached there is a sudden drop in the floor of the sea. The manner in which this marine shelf is carved out of the land will be easily understood by a reference to fig. 37.

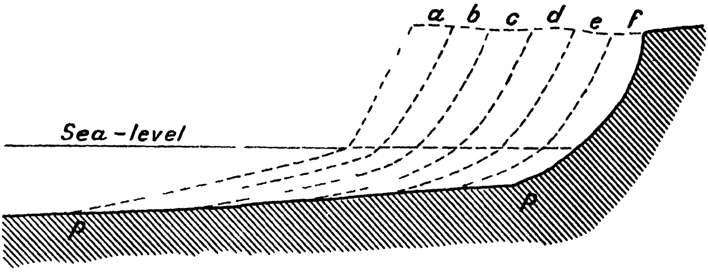


FIG. 37.—Showing formation of plain of marine denudation

a, *b*, *c*, *d*, *e*, and *f* are successive slices shorn off the edge of the land forming the marine plain *p p*

Where the land fronting the sea is high, the shelf is usually narrow, and where low it is relatively wide But the total amount of erosion is probably about the same everywhere, for the greater height and less width in one place will balance the less height and greater width at another

Where the land has been recently elevated, the remains of ancient plains of marine denudation can still be clearly traced as raised benches or platforms contouring around the shore

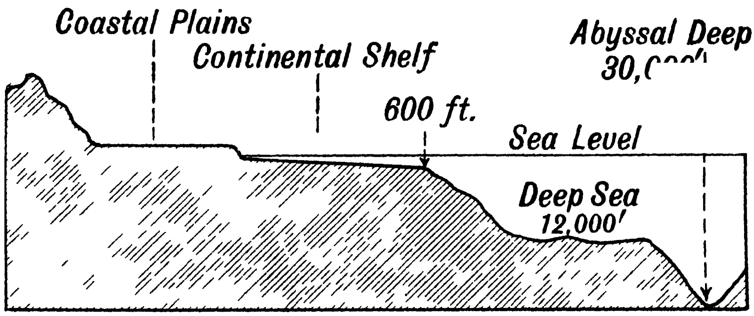


FIG. 38.—Showing section of continental shelf.

The Sea as a Constructive Agent.

Effects of Sea-Currents.—The great oceanic currents do not reach the bottom, and therefore possess little or no power either to transport detritus or to erode the floor of the sea ; but many coast-lines are swept by currents that hug the shore and run in one direction during the whole or greater part of the year. These littoral currents may be termed rivers of sea-water, and, like freshwater rivers, they are important agents of transport and erosion.

The gravel, sand, and silt discharged by a stream or river into the head of

a sheltered bay, inlet, or land-locked harbour is spread out on the bottom, where it gradually accumulates, till in time it fills up extensive areas which are thus reclaimed from the sea. It is in this way that the alluvial flats and deltas that are found fringing the head of so many bays and inlets have been formed.

But where the stream or river discharges its load into the open sea, the detritus is picked up by the coastal currents and spread over the sea-floor, or piled up on distant strands, perhaps scores or even hundreds of miles from the river mouth. In this way vast quantities of detritus are daily moved from one place to another.

Only the fine silt and mud is carried in suspension. The bulk of the material in the form of sand or shingle is trailed or rolled along the sea-floor, and in consequence exercises a powerful erosive effect on all submerged reefs and ledges, on outlying islands, and projecting headlands. The travelling sands and shingles possess the same rasping and eroding effect as the moving sands and gravel on the floor and sides of a river-channel.

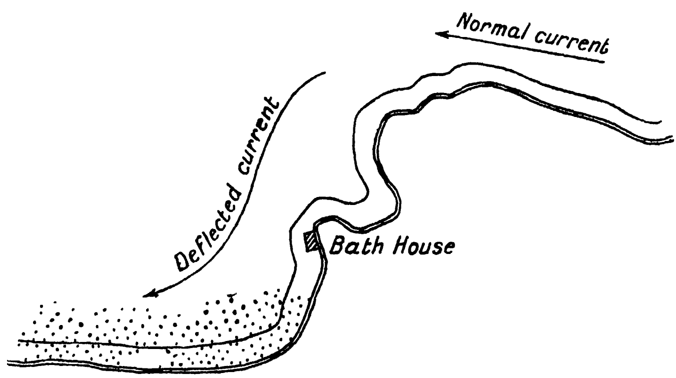


FIG. 39.—Showing piling up of sea-borne sand on sheltered side of headland of St. Clair, Otago.

Sea-borne sands usually accumulate on the sheltered side of headlands or in bays, where they form sand-banks that are sometimes awash or bare at low-water. In many places the wind piles up the sands thus placed within its reach into dunes and ridges running parallel with the beach.

The coastal currents of Otago travel northward all the year round. They strike Black Head at St. Clair, and are diverted seawards for some distance; but during southerly gales they are deflected inshore, with the result that many millions of tons of sea-borne sand are sometimes thrown up on the beach in the course of a few hours, frequently covering up the protecting groins as shown in fig. 39.

But when south-east gales prevail, the sea, instead of piling up sand, becomes destructive and erodes the sandhills with destructive effect to the public domain.

Where two coastal currents travelling in different but converging directions meet one another, their impact causes their rate of flow to be diminished or altogether destroyed along the line of contact, with the result that the sands they carry are allowed to settle and accumulate along that line, where they eventually form submerged sand-banks and long sand-spits. A notable example of this class of constructive work is found at the extreme north-east

corner of Nelson. Here a spit of sand, 20 miles long, has been formed by the converging Farewell and Golden Bay currents as shown in fig. 40.

In Europe we have the banks forming the chain of Fresian islands, beginning with the Texel and ending near the mouth of the Weser River. They are 200 miles long, and in the western part form the outer barrier of the Zuider Zee. Other good examples of sand-spits are Hela Peninsula and Frische Nehrung in the Gulf of Danzig, the Kurische Nehrung, north of Königsberg, and the famous Tongue of Arabat that divides the Putrid Sea from the Sea of Azov.

Perhaps the best examples of coastal spits and banks are to be found on the east coast of the United States. On the coast of New Jersey we have Island Beach Spit, 25 miles long, and Long Beach the same length. In North Carolina, a sand reef fringes the coast from Virginia Beach to Cedar Point, a distance of 180 miles; and another spit of nearly the same length extends along the Florida coast from near Harwood in the north to Palm Beach in the south.

The passage leading to the lagoon enclosed by a sand-spit is usually protected by a *sand-bar* that may be awash or even bare at low-water. If the bar

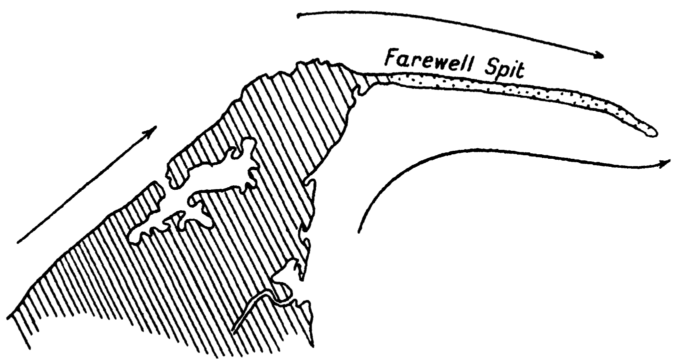


FIG. 40.—Showing formation of sand-spit by two converging sea-currents at Cape Farewell, N.Z.

is raised by the piling up of sand so as to exclude the sea, except perhaps at the highest spring tides, we get a *natural salt-pan*, and if the region is arid sheets of salt may accumulate on the floor of the lagoon, alternating at the edges with layers of sand.

Of natural salt-pans, the Rann of Cutch on the north-west coast of India is a typical example. It is a low-lying coastal area, flooded during the south-west monsoons in some parts to a depth of three feet, and is a true salt-plane. Similar salt-pans or *salinas* occur on the coasts of the Red Sea and the Nile delta.

Beach-Cusps.—These are triangular ridges of sand or beach shingle that, as a rule, extend landward at right angles to the shore-front. On long beaches these *giant ripples* may occur at nearly regular intervals for a distance of a mile or more. A cusp may rise from an inch to several feet above the general level of the beach, and it may be low or steep-sided. Sand-cusps are more common than those of shingle.

Many suggestions have been made as to the origin of beach-cusps, but their origin still remains obscure. They may be formed by the rhythmical swash of the waves striking the beach obliquely, the sand being piled up by the middle part of the wave curving round after its end had grounded on the shore and hence lost its momentum.

After storms the truncated ends of the cusps stand up in clear relief along the beach.[1] What are thought to be fossil-cusps have been recognised in some sandstone formations, notably in the Medina sandstone of western New York.[2]

Littoral Shingle Deposits.—These may be divided into three classes, according to their form and origin, namely (1) the fringing beach, (2) the shingle-spit, and (3) the shingle-flat.

The *fringing beach* is the simplest and most common type. It consists of

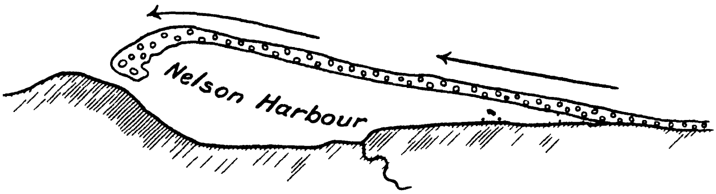


FIG. 40A.—Boulder Bank, Nelson, N.Z.

a strip of shingle along the strand, formed by the coastal currents directed at right angles against the shore.

The *shingle spit* is a deposit of shingle beginning at the point where the coast line suddenly changes its direction and turns inwards, while the current running along it still pursues its course past the point of deflection. The drifting shingle accumulates along the course of the current, and in time forms a bank or causeway that may be many miles long. The bank frequently curves inwards at its growing end. Good examples of shingle spits are the Chesil Bank, which runs parallel with the coast of Dorsetshire for 15 miles, and the Boulder Bank, at Nelson, a gigantic causeway, 12 miles long, which encloses a deep, well sheltered harbour (fig. 40A). When the bank grows till it again touches the land it forms a *bar*.

Above high water mark, the shingle is often piled, by high tides and storms,

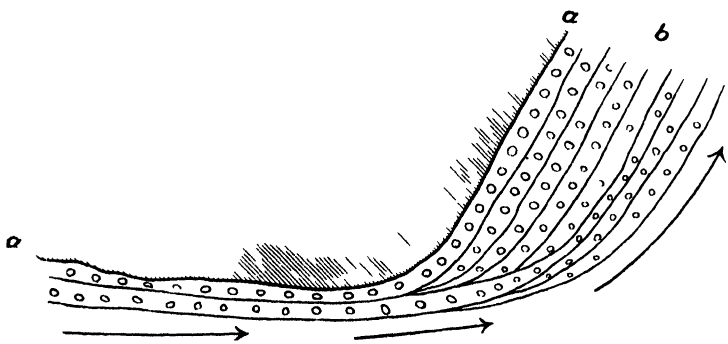


FIG. 40B.—Showing formation of marine shingle flat.
(*a*, *a*) Old shore line. (*b*) Shingle flat.

into a low mound running parallel with the shore, forming what is called a *storm-beach*.

The *shingle flat* is formed when the coastal current, due to some local cause, follows the inward trend of the deflected coast line, the shingle being

[1] J. F. Kemp, "Observations on a Florida Sea beach with reference to Oil Geology," *Economic Geology*, No. 4, vol. xiv., 1919, pp. 312–316.
[2] J. C. Bonner, "Origin of Ripple Marks," *Jour. of Geol.*, vol. ix., 1901, pp. 535–536.

deposited as a succession of parallel banks. In this way large areas may be reclaimed from the sea (fig. 40B).

Sorting and Spreading Action of the Sea.—The gravel, sand, and silt discharged into the sea by streams and rivers are sorted by the laving action of the waves into three main grades of different sizes. The shingle is spread along

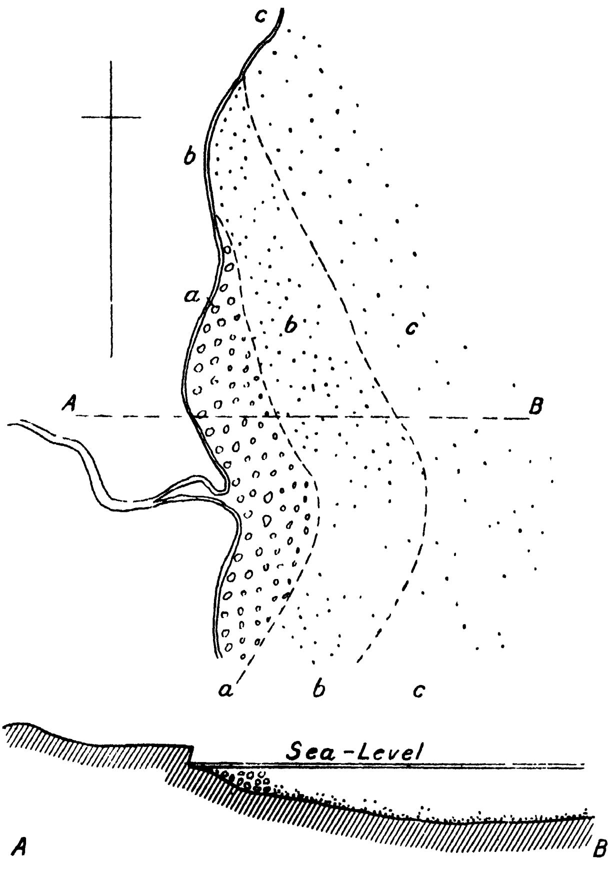


FIG. 41.—Plan showing lenticular distribution of gravel, sand, and silt on coast-line.

(*a*) Gravel. (*b*) Sand. (*c*) Silt and mud.
A B, Line of section at right angles to shore-line.

the shore in the shallow water, the sands are distributed over the sea-floor for many hundred yards on the seaward side of the shingle, while the silts and muds are transported still further seaward.

We have thus three zones of deposition running approximately parallel with the shore and with one another. There is seldom a sharp line of demarcation between the different zones. More often the one graduates insensibly into the next; but the extremes are always clearly defined. Thus the clean gravel is easily distinguished from the sand, and the sand from the silt and mud.

Beginning with the shore-line deposits we have thus:

(1) The shingle and gravel zone.
(2) The sand zone.
(3) The silt and mud zone.

Where the deposition takes place without disturbance from currents, we can usually distinguish six grades of material that insensibly pass into one another, namely:

(1) Shingle.
(2) Gravel.
(3) Sandy gravel.
(4) Coarse sand.
(5) Fine sand.
(6) Silt and mud.

Lenticular Form of Marine Deposits.—The different zones of material starting from the point of discharge are nearly always found to be more or less lenticular in form. It thus happens that in passing along the coast-line we encounter the same succession of gravel, sand, and silt as we do by following a line running at right angles to the shore-line. Thus, as shown in fig. 41, we find that the beds *a, b, c,* found along section line *A B*, are the same as beds *a, b, c* that successively abut against the shore-line in passing northward from the point of discharge.

Formation of Deltas.—Streams and rivers that are sluggish in their rate of flow are only able to transport sand and silt to the sea. In the absence of

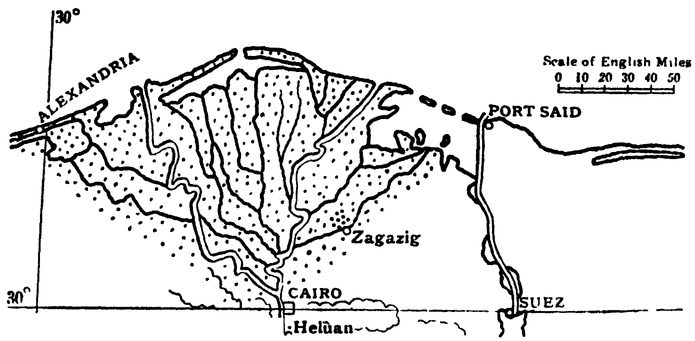


FIG. 42.—Plan showing delta of the Nile in Egypt.

coastal currents the sands and silts are deposited at the mouth of the river, where they accumulate till they form obstructing banks through which the river flows in numerous intricate shallow channels. By the piling-up action of the wind at low-water, and by the deposit of sand and silt during times of flood, many of the sand-banks rise above ordinary water-level. When this happens vegetation soon establishes itself, and a *delta* is thus formed.

Estuarine Deposition.—In marine deposition, as we have seen, the coarsest material is laid down nearest the shore-line, and the finest furthest seaward; each zone of graded material being spread over a lenticular or meniscus-shaped area. In estuarine deposition this arrangement is reversed, the coarsest material being deposited at the entrance and the finest at the head of the estuary.

At the entrance the tide usually rushes in with great velocity. When once inside the harbour the tide as it advances spreads over an increasing area, with the result that its rate of flow shows a corresponding decrease.

The result of this gradual slackening of the current is that the coarsest material is deposited at the entrance, and the finest at the extreme limits reached by the tide.

In places where the coastal currents transport gravel, sand, and mud, the incoming tide deposits first gravel, then sand, and lastly mud ; the first at the entrance and the last in the upper reaches of the estuary. Where the tide carries only sand and mud, as is so frequently the case, the sand is deposited at the entrance and the muds inside. Hence we find that the entrance of some estuaries is protected by a bank of gravel, and of others by shoals and bars of sand. In many cases the sands deposited inside the estuary are piled by the wind into dunes and ridges running parallel with the coast-line.

The area covered by the gravels is commonly narrow. On the other hand, the sands are deposited over a wider belt, but even this is relatively small in extent compared with the mud-covered area. The limited distribution of the coarser material is due to the rapidity with which the current of the inflowing waters diminishes when once the waters begin to spread over the banks and shoals of the estuary.

In some of the great estuaries and tidal harbours of northern and south-east Australia the mud covers hundreds of square miles, while the sands near their entrance occupy but a relatively narrow belt. In these shallow harbours the tidal waters come in laden with mud and retire laden with mud, but each tide as it slowly creeps over the mud-banks deposits a thin coating of sediment which imperceptibly but steadily raises the mud-covered area till it is high enough to enable a semi-aquatic vegetation to establish itself on its surface. In this way these tidal inlets are being gradually filled up and reclaimed from the sea.

Nearly all estuaries receive the drainage of one or more rivers. Some of the larger streams discharge a load of gravel and sand into the estuary, where it is spread out and mingled with the fine harbour muds. In this way we frequently get the curious spectacle of gravels and sands mingled with almost impalpable mud, or intercalated with layers of mud.

Marine Organic Deposits.—The floor of the deeper or abysmal portions of the sea has been shown by soundings to consist of a fine calcareous ooze mainly composed of the tiny shells of *Foraminifera*, etc.

On their seaward limits, the fine mechanical sediments reaching out from the land mingle with this ooze, forming deposits which become, when hardened, what are called *chalky clays* or *chalky marls*. The ooze itself, when free from terrigenous matter, forms, when consolidated, a limestone resembling *chalk*. These organic oozes will be described more fully in the succeeding pages.

Time-Plane of Deposition.—Going seawards, the coastal gravels graduate into sands, the sands into muds, and the muds into calcareous ooze. The gravels, sands, muds, and ooze were deposited at the same time and lie on the same plane or sea-floor, forming a wedge-shaped deposit that tapers seaward. Sediments deposited contemporaneously on the same floor constitute what is called a *time-plane of deposition*.

Faunal Differences in Same Plane.—Each grade of material will be distinguished by the forms of life that prevailed in the zone in which it was laid down. That is, the gravels will contain the broken and rolled remains of such littoral shells as oysters, mussels, and cockles ; the sands, the remains of *Pinna*, *Tellina*, and other fragile shells ; the muds, minute molluscs, and

Foraminifera; while the ooze will consist mainly of Pteropods and various *Foraminifera, among which the genus Globigerina will be the commonest.*

A change in the character of the deposits is usually followed by a change in the fauna; but with a recurrence of the same sediments there will frequently be a reappearance of the displaced fauna; and if, in some places, the lithological character of the deposit remains unchanged, some species may persist in that place into a higher horizon than is usual elsewhere.

Besides the faunal differences due to the various character of the sediments, it is found that certain organisms inhabit shallow, and others deep water. Hence it must be remembered that faunal differences in the same plane may arise as much from *influence of station* as from differences in the texture of the sediments.

The depth of the sea normally increases with the distance from the land, but great depths may be obtained in certain conditions quite close to the land, as in the fiords of Norway and New Zealand, where a depth of 100 fathoms may frequently be found a few yards from the shore. In such situations we are liable to find a curious commingling of littoral and deep-water species.

Some organisms find a congenial habitat in muddy waters, others in clear; some flourish only on rocks and reefs, or on mud banks, exposed between the upper and lower tide-marks; and while some prefer still, clear waters, others can only exist in situations exposed to the break of the ocean-waves.

Differences of latitude, with the attendant differences of temperature, exercise a powerful influence on the character of the marine fauna. In New Zealand, which runs through 700 miles of latitude, the differences that distinguish the molluscous fauna of Southland and Cook Strait, and of Cook Strait and North Auckland, are almost startling. And perhaps no less potent than latitude is the influence of oceanic currents, as witness the widely different faunas of Labrador and Ireland arising from the Gulf Stream.

We have no reason to believe that faunal differences in the same geographical plane were relatively less conspicuous in past geological ages than they are to-day; hence, when carrying on palæontological research, we must always bear in mind that the most diverse faunas may be co-existent on the same geographical plane. These faunal differences tend to render the correlation of distant formations of doubtful value. In every case due allowance must be made not only for differences of station but also of latitude.

Classification of Marine Deposits.—Marine deposits, according to their distance from the land, may, for convenience of descriptive purposes, be divided into four natural zones:

(1) *Littoral*[1] *Zone*, including pebbly, sandy, and coralline deposits.
(2) *Thalassic*[2] *Zone*, including fine sediments, such as muds and silts.
(3) *Pelagic*[3] *Zone*, including accumulations of calcareous ooze.
(4) *Abysmal*[4] *Zone*, including Red Clays of volcanic and cosmic origin, and the radiolarian oozes.

Varying Thickness of Marine and Estuarine Deposits.—From what has been said in the preceding pages it will be obvious that all the detritus discharged into the sea, as well as the material derived from the erosion of the land by marine agencies, is sorted and spread out as a sheet on the floor of the sea. The thickness of this sheet is greatest along the shore-line, and least towards

[1] Lat. *litus*=sea-shore.
[2] Gr. *thalassa*=sea, *i.e.* shallow sea.
[3] Gr. *pelagos*=sea, *i.e.* deep sea.
[4] Gr. *abyssos*=bottomless.

the deeper sea. Thus, if a thick bed of coastal gravel is traced seaward, it will be found to taper rapidly till it dwindles down to a thin layer that eventually passes into the sandy zone, which in turn thins out till it passes into silt and then mud.

The different layers of estuarine sediments are also wedge-shaped in cross-section, being thickest at the lower end near the entrance, and least at the upper end of the estuary.

It should, however, be remembered that the distribution of both purely marine and estuarine sediments is liable to considerable variation through the disturbing influence of coastal currents in respect of the first, and of large streams or rivers in respect of the second. Disturbance from the sea-currents is, perhaps, of commoner occurrence than disturbance from rivers, as in the case of large estuaries or mediterranean seas, the effects of the inflowing streams will be mainly local, or confined to the margin of the greater sheet of fine sediments. *Wash-outs* that take place during abnormal floods are often filled in with coarse, gravelly sands, or, at any rate, with material differing from that deposited in normal conditions.

The Sea as a Source of Life.—It is almost certain that the first forms of plant and animal life were aquatic or marine ; and it was probably in the sea that the first steps in the evolution of the more highly organised forms took place. The sea, ever since the beginning of geological time, has been the universal cradle and preserver of life. Earthquakes and volcanic eruptions might devastate the dry land, but in the sea, life always found a safe asylum.

Around the shores of islands and continents in the comparatively shallow water, the sea is very prolific in molluscous life. The molluscs manufacture their shells from carbonate of lime secreted from the sea-water, and where they grow in colonies, their shells frequently accumulate till they form shell-banks of great extent. Many shelly limestones that now form hard rocks are composed of shells that grew on shell-banks on the floor of a shallow sea.

The coral polyp in the warmer seas of the tropics builds up reefs of coral that in time become converted into solid limestones.

The Sea as a Highway.—The sea stretches over the whole globe and therefore affords an easy means of migration for all kinds of marine life. The sea-currents also carry seeds and seed-spores from place to place, and thus enables vegetation to spread to new islands or to islands that have been devastated by volcanic eruptions. The comparative rapidity with which sea-borne plants may reclothe an isolated land is well illustrated at Krakatoa. In 1883 that island was overwhelmed with volcanic ejecta which destroyed all the plant and animal life. In less than twenty years the island was reclothed with a dense jungle from seeds carried to its shores by sea-currents. The same rapid dispersal of plants doubtless took place through all the past geological ages.

Fossils.—Sediments laid down on the floor of the open sea contain the imbedded remains of marine plants and shells, the bones and teeth of fishes and other creatures that lived in the sea. From a study of these fossil remains we are able to construct a picture of the depth of the sea and climatic conditions prevailing at the time the sediments were laid down.

Sediments laid down in estuaries, tidal harbours, and deltas are found to contain the bones and teeth of land animals whose bodies were washed into the sea, the shells of land and fresh-water molluscs, the trunks of trees, as well as seeds, nuts, twigs, and leaves. With these are mingled the remains of animals that frequent the brackish waters of deltas and estuaries, together with those of marine organisms washed up by sea-currents and tides.

The mingling of land, fresh water, brackish water, and marine forms is characteristic of deposits that were laid down in estuaries and mediterranean seas.

Variations of Sea-Level.—Up till the beginning of this century it was the general belief that the level of the sea was invariable, and any departure from this view was looked upon as a geological heresy. All transgressions of the sea on the dry land were regarded as an evidence of actual subsidence of the land; and all recessions of the sea as proofs of uplift. Uplift and subsidence of the land have taken place in all geological ages, both local and continental, of small amount and of great magnitude, as the result of crustal folding or of volcanic or earthquake disturbance. It is obvious that no movement of the crust, whether it affects the sea-floor or dry land, can take place without a corresponding displacement of the sea-level. When a portion of the ocean-floor sinks, the sea recedes from the dry land, and the effect is the same as an actual uplift of the land. Conversely, when a segment of the ocean-floor rises, the sea-level is correspondingly raised, and we get a transgression of the sea producing an effect similar to an actual sinking of the land.

But the sea covers such a large part of the surface of the globe that any changes of its level produced by the rising or sinking of crustal segments must be relatively small compared with the local effects. If the continent of Australia, due to crustal collapse, were to sink 500 feet, a large part of its surface would be invaded by the sea, but the displacement caused by the submergence would raise the general sea-level datum less than 10 feet. It is difficult to escape the conclusion that the great transgressions of the sea recorded in geological history were the result of displacement arising from crustal movements.

A condition that must always exercise a dominating influence on the rate of transgression is the steepness of the shore-line. If the coast were bounded by steep cliffs the transgression would be slow, and perhaps for some time imperceptible. The rate of sinking, the supply of detritus, and the steepness of the sea-floor are important factors in determining the position of littoral deposits.

Deposition during Uplift and Subsidence.

The sediments laid down on the floor of the sea and in great estuaries are the materials of which sedimentary rocks are formed. When, therefore, we are able by actual observation to see how such deposits are laid down at the present day, we are confronted with fewer difficulties in our study of the rocks formed under similar conditions in past geological ages. In other words, the better we understand the first principles governing the deposition of sediments in lake estuary, and sea, the better will we be able to grapple with the problems presented by the varying texture, distribution, and fossil contents of sedimentary rocks. The present conditions afford the key to the past; hence we must study present conditions in order to understand the past.

Effect of Deposition on a Rising Sea-Floor.—When a general uplift of the land takes place, the shore-line advances on the sea, with the result that the sediments are, as previously described, carried further and further seaward, thereby causing *seaward overlap* whereby gravels may be deposited on sand, sand on mud, and mud on the pelagic calcareous ooze.

If the uplift is rapid and persists for a considerable time, the overlap will be more and more marked, and thus it may happen that pebble and sand beds may be eventually deposited over the calcareous ooze, the pelagic zone being now a shallow sea.

But to return to the first case where the first effect of the uplift is just sufficient to permit the sands to overlap and spread over the mud. It may happen that the uplift is followed by subsidence. In this case the shore-line will advance on the land, and the overlap will be landward, thereby permitting mud to be laid down on the newly formed sands.

The succession of sediments in the deeper zone of deposition will now be mud, sand, mud.

If the land is oscillating with approximate regularity, we shall get many alternating layers of sand and mud. And since the deposition of mud is relatively slower than that of sand, the layers of sand will be thicker than those composed of mud.

Geographical Effect of Uplift.—If the upward movement continues, the partially land-surrounded portions of the sea will be at first converted into *mediterranean* seas, and eventually into inland lakes. If this takes place in an arid region, the evaporation of the water will leave a deposit of salt on the floor of the dried-up basin. When the infilling of the lake-basin takes place, as the result of physical and climatic changes, the deposit of salt will be covered with layers of sediment that will protect it from destruction. It was doubtless in this way that the valuable deposits of salt in England and Continental Europe were formed.

Deposition on a Stationary Sea-Floor.—On a stationary sea-floor there will be a slow advance of the shore-line. The near-shore deposits will tend to obstruct cliff-cutting, and the shore deposits will spread seaward till the outward limits of wave transport are reached. As a result of inshore deposition coastal plains will be reclaimed from the sea and valley-deltas will be formed.

Simultaneous Deposition and Erosion during Uplift.—When uplift takes place the sediments first laid down around the shore are raised into a position where they become subject to subaerial and marine denudation; and being for the most part loose and incoherent, they are easily broken up and removed. But the mere uplift of the land does not stay the activity of the processes of denudation that were in operation before the uplift began. On the contrary, the rate of denudation may be accelerated, as the obvious effect of the uplift will be to increase the gradient of the slopes, whereby the erosive power of the streams and rivers will be correspondingly increased.

So long as the uplift continues, the ordinary products of denudation *plus* the material derived from the breaking up and re-sorting of the coastal sediments, which are now subject to denudation as the result of the uplift, are carried further seaward and spread out as a sheet that overlaps, but lies parallel with the sediments laid down before the uplift began.

Thus we see that while uplift may cause the landward edges of the first and consequently oldest layers of sediment to be worn away and re-sorted, deposition will still be in progress in the seaward direction. Moreover, there will be no physical break in the continuity of the layers which will follow one another in a *conformable* sequence or succession. That is, the layers will all lie in the same plane, like the slates or wooden shingles on the roof of a house, except at the landward side where the newer sediments will lie on the travelled edges of the older. Elsewhere there will be no stratigraphical unconformity to mark the interval of time occupied in the uplift and following subsidence. Though there may be no physical discordance in the succession, there will be a faunal break arising from change of station, and the time occupied in the uplift.

Deposition during Subsidence.—The transgression of the sea that accompanies subsidence raises the level of the sea relatively to the land, thereby diminishing the elevation of the land and the area subject to denudation.

The land detritus that was formerly deposited far off-shore is now laid down near-shore.

During subsidence the sea advances on the land, and the overlap of the sediments is *landward*. In the process of time the subsidence of the land permits coastal valleys to be submerged and estuaries to be formed. The piles of sediment that constitute the great geological systems were formed during downward movement. The effect of frequent oscillations of the land—that is, of alternating uplift and subsidence—is to pile up alternating layers of off-shore and near-shore sediments upon one another.

It is obvious that great thicknesses of uniform sediments can only be laid down on a sinking sea-floor where the rate of deposition and sinking are the same, so that the depth of the water remains constant. The overloading of the sea-floor is generally believed to be the cause of subsidence and consequent crustal folding. Dana postulated that zones of folding begin their existence as long narrow depressions in which piles of land sediments are accumulating, and for such depressions he suggested the name *geosynclinals*.

The Cycle of Deposition.—The typical succession of sediments of many geological systems begins as a basal conglomerate and closes with a limestone, the complete sequence being (*a*) basal conglomerate, followed by (*b*) marine sandstones, (*c*) clays, and (*d*) limestone in ascending order. This succession is obviously the result of deposition on a sinking sea-floor.

The torrent-formed gravels composing the basal conglomerate were probably transported by streams from a terrain of high or moderate surface-relief. On a stationary or slowly rising sea-floor the gravels would be carried further and further seaward till they eventually reclaimed a maritime belt of land from the sea. This belt would be flat, swampy, and probably deltaic.

At this stage a general subsidence set in; and as the downward movement continued, the sea encroached further and further on the land. The terrestrial gravels thereby in time became covered with marine sands, the sands with muds, and the muds with a layer of calcareous organisms that, when consolidated, formed the closing limestone member of the series.

Seams of coal are frequently found associated with basal conglomerates, from which it may be deduced that, during the deltaic period, vegetation established itself on the mud-flats, and grew so rank and rapidly that sufficient vegetable matter accumulated to form valuable seams of coal.

Each seam of coal marks an old land surface, and when we find that the different seams are separated by beds of sandstone or conglomerate, we are able to conclude that the land was slowly oscillating during the deltaic period; that is, before the general subsidence began that led to the terrestrial gravels and their seams of coal being buried beneath the succession of marine beds.

The effect of progressive subsidence is to reduce the height of the dry land; while the continuous denudation tends to reduce its surface to contours of low relief. Should the subsidence continue, the land will eventually become submerged. While the subsidence continues, the sediments spread out on the sea-floor overlap more and more. Where there is total submergence of the land we may even find a calcareous zone or limestone riding hard on the basement rock as the result of profound overlap.

Pelagic Organic and Deep-Sea Deposits.

We have seen that, as we leave the land, the materials spread out on the sea-floor become progressively finer and finer in grain, till a limit is reached

beyond which the sea is quite clear and free from sediment derived from the land.

Pteropod Ooze.—The deep-sea dredging carried out by the *Challenger* Expedition showed that, from the outer edge of the mud zone down to a depth of about 1500 fathoms, the sea-floor is covered with a calcareous ooze consisting mainly of the shells of *Pteropods* and *Foraminifera*, the former very small molluscs, the latter minute protozoans that live in beautiful chambered shells full of small pores ; hence the origin of the name. In this zone the Pteropods predominate. Oozes with predominating Pteropods, the real "Pteropod oozes," do first occupy large areas on the recent sea-floor.

Globigerina Ooze.—From about 1500 fathoms down to 3000 fathoms, the sea-floor is covered with a calcareous ooze consisting almost entirely of the shells of Foraminifera, the commonest of which is *Globigerina*, from which this ooze is named.

Red Clay.—At greater depths than 3000 fathoms the calcareous oozes are absent, their place being taken by an excessively fine deposit called *red clay*.

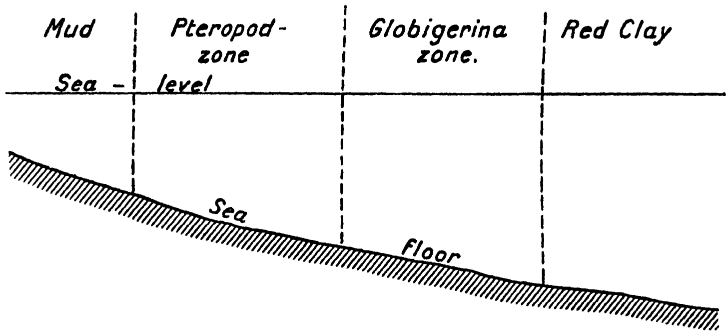


FIG. 43.—Showing zones of calcareous ooze and *red clay* in the abyssal depths of the sea.

The *red clay* would appear to be fine dust that has fallen on the surface of the sea. It consists partly of fine volcanic dust, and partly of wind-borne desert dust, mixed with what is believed to be the dust of meteors that have been broken up on entering our atmosphere. The principle constituents are silica, iron and manganese peroxides, and alumina. Most of the common and some of the rarer minerals are also present.[1]

This dust, from whatever source it is derived, is small in quantity, and when spread over the many millions of square miles of the sea-floor, must take thousands of years to form a layer even an inch thick.

The surface of the *red clay* is thickly scattered with the teeth of sharks, hundreds of which have been skimmed up by the dredge and brought to the surface. These teeth belong in part to forms characteristic of the Tertiary formations and are so numerous that it must have taken an extremely long time for them to accumulate, and yet the *red clay* has not been able to cover them, so slow is the rate at which it is being deposited.

Cause of Zonal Arrangement of Calcareous Organisms.—Both the *Pteropods* and *Foraminifera* are organisms that swim about freely at the surface of the sea. They exist everywhere in countless millions, and there is a continual rain of their dead shells as they slowly fall through the water.

The empty calcareous shells of both the Pteropods and Foraminifera are

[1] Sir J. Murray and Renard, "*Challenger*" *Reports, Deep-Sea Deposits*, 1891, p. 204.

soluble in sea-water; and where the depth of the ocean exceeds 3000 fathoms both are dissolved before they reach the sea-floor. Hence the absence of these organisms in the *red-clay* zone.

Pteropods are absent from the *Globigerina* zone because their shells, being more delicate, are more soluble than those of the Foraminifera. Therefore, although the dead shells of both Pteropods and Foraminifera begin their long downward journey together, when a depth of 1500 fathoms is reached, the Foraminifera are left to continue the journey alone, the shells of the Pteropods having passed into solution in the sea-water. The very thin parts of the shells of the Foraminifera are, however, usually dissolved.

Pteropods and Foraminifera are abundant near the shore in all classes of sediment, but they are not easily seen except when samples of the mud and sand are carefully washed.

The calcareous ooze of the deep sea is the material of which the chalks and limestones of some future time will be formed.

Radiolarian Ooze.—This ooze, which also contains numerous *Diatoms*, is not found so widely spread as the *red clay*, which covers the greater portion of the sea-floor below the 3000-fathom line. At the greatest depths known in the Pacific Ocean the *red clay* contains deposits of Radiolarian ooze. The Radiolaria as well as the Diatoms live at the surface of the water, but as they are composed of silica, which is but feebly soluble in sea-water, they are able to reach the bottom even at the greatest depths.

Radiolarians have been important rock-forming organisms from almost the earliest Palæozoic time. They constitute a large proportion of many Palæozoic cherts and siliceous limestones in both Hemispheres. Notable among radiolarian beds in Great Britain are the cherts intercalated in the Ordovician Mylor series of South Cornwall, which are in places full of Radiolaria.[1]

Perhaps the greatest known thickness of radiolarian rock occurs in the Tamworth district, New South Wales, where radiolarian cherty shales with interbedded radiolarian limestones and tuffs of Lower Devonian age attain a thickness of 4150 feet.[2]

Diatom Ooze.—Like the radiolarian ooze the diatom ooze is a siliceous deposit. It consists preponderantly of the frustules of diatoms, which are tiny plants (Algæ). The geographical range of this diatomaceous ooze is especially the Antarctic Sea, south of the fiftieth parallel of latitude. The more delicate frustules of the diatoms do not reach the sea-floor, for they are dissolved on their journey to the ocean-floor.

SUMMARY.

The Sea as a Destructive Agent.

(1) The erosive work of the sea is *chemical* and *mechanical*.

(2) The free carbonic acid contained in sea-water converts limestones into the soluble bicarbonate of lime; dissolves the binding medium in all kinds of calcareous rocks; and attacks the felspar of igneous rocks, such as granite and basalt. Limestones are thus slowly worn away, while calcareous and igneous rocks are first disintegrated and then destroyed.

[1] J. B. Hill and D. A. MacAlister, "The Geology of Falmouth and Truro," *Memoirs of Geol. Surv. England and Wales*, 1906, p. 18.

[2] T. W. Edgeworth David and E. F. Pittman, "Radiolarian Rocks of New South Wales," *Quart. Jour. Geol. Soc.*, 1899, p. 36.

The free oxygen in the sea-water continues the disintegration effected by the carbonic acid by oxidising the iron in the iron-bearing minerals.

(3) The greatest erosive effect of the sea is the work of the tides, sea-currents, and waves set in motion during storms. In this way the edge of the land is gradually eaten away, the softer rocks being shorn back, while the harder are undermined till they finally become shattered and broken up. The blocks of hard rock accumulate at the foot of the cliffs, where they at first form a protecting apron, but are afterwards broken up and rounded, in time forming shingle, and finally sand and silt. During great storms blocks of hard rock are flung with destructive effect against the cliffs.

(4) Soft rocks are worn away more rapidly than hard; thus in time the former are worn back till they form bays and gulfs, while the hard rocks remain as steep cliffs and projecting headlands.

(5) In high latitudes masses of floating ice abrade the rocks, and may even wear away the edge of the land into benches.

(6) The recession of a coast-line shortens the course of streams and rivers, which are thus enabled to regrade and cut down their beds. In this way rivers, in the process of cutting down their beds, may excavate terraces in the lower portion of their course, the effect of recession being the same as an elevation of the land.

The submarine shelf or platform, that surrounds all the continents, may be a rock-platform or composed of land detritus. From the shore to the outer edge the slope is gentle. Beyond this the sea-floor descends abruptly to great depths. At the outer rim the depth of water varies from 300 to 600 feet. The shelf is generally regarded as the submerged outer margin of the continents. The submersion may be the result of a rise of the sea-level or of a subsidence of the continents. The former explanation appears to be the more probable.

(7) The total effect of all the processes of marine denudation is the cutting away of the land to an even platform called a *plain of marine denudation*. Nearly all large islands and continents rise from a marine shelf or platform of this kind, as shown by soundings around their shores.

The Sea as a Constructive Agent.

(8) The sea is the final destination of nearly all the products of denudation of the dry land. Streams and rivers continually discharge an enormous load of gravel, sand, and silt into the sea, where it is sorted and spread out, the coarser material near the shore, the sands in deeper water, and the silts and muds still further seaward. Many harbours and bays in time become filled with detritus, and in favourable situations sand-banks and shoals of sand may be formed far out from the land. Converging sea-currents may form sand-spits of great length.

(9) In estuarine deposits the coarsest are laid down near the entrance, and the finest at the utmost limits reached by the flowing tide. Where streams discharge coarse material into the estuary, these are mingled with fine harbour muds.

(10) The sea is the cradle and preserver of life. By its great extent it affords unrivalled means for the migration and dispersion of land plants, and all kinds of marine life.

(11) The remains of plants and animals are embedded in deposits of all kinds—marine, estuarine, fluviatile, lacustrine,—and there preserved from destruction. They form valuable records of the contemporary life, climate, and physical geography of the period of deposition.

(12) *During uplift of the land rivers deepen and regrade their channels, and marine sediments are carried further and further seaward, whereby* ***seaward overlap*** *takes place.*

(13) The geographical effect of continued uplift is to convert partially land-surrounded portions of the sea into seas of the *mediterranean* type, and eventually into land-locked basins or lakes, in which, by evaporation, deposits of salt may be laid down.

(14) During uplift, deposition of sediments continues without cessation, the sediments being merely carried further and further seaward. But while this is taking place, the upward movement of the land raises the old shore-line above sea-level, with the result that the coastal edges of the sediments first laid down are subject to the wear and tear of subaerial and marine agents of denudation. The shoreward portions of these older layers are thereby broken up, re-sorted, and spread out on the sea-floor along with the ordinary products of subaerial denudation. Thus we see that deposition and erosion may proceed at the same time during uplift of the sea-floor.

(15) During subsidence the sea encroaches on the land, and the sediments overlap one another in a *landward* direction. It is probable that all the piles of sediments forming the great geological systems were laid down during downward movement of the land.

(16) In a typical cycle of deposition we find that gravels, sands, and muds shot down on a stationary or slowly rising sea-floor in time reclaim a maritime belt from the sea, producing conditions that are frequently deltaic. When progressive subsidence takes place, these terrestrial deposits are covered over with marine sands, followed by marine muds. These may be followed by a layer of calcareous organisms that, when consolidated, will form a bed of limestone which will close the cycle of deposition. In other words, the cycle begins with a deep-sea deposit, provided the subsidence is continued.

During the deltaic period, if the climatic conditions are favourable, rank vegetation may establish itself on the level swampy coastal lands, and if it remains long enough, sufficient decaying vegetable matter may accumulate to form valuable seams of coal. When the general downward movement begins, this vegetable matter will be covered over with sands and other sediments, and thereby protected from destruction.

The presence of two or more seams of coal would indicate that the land was slowly oscillating during the deltaic period—that is, before the general downward movement was fairly started.

(17) The pelagic deposits of the sea consist of various calcareous oozes that below the 3000-fathom line give place to the abysmal *red clay*, composed of volcanic, desert, and meteoric dust that settled on the surface of the sea.

(18) The continuous growth of coral in warm tropical seas forms large masses of calcareous rock, which, by the infiltration of calcareous waters, assume a crystalline structure resembling the older Palæozoic limestones.

Other calcareous organisms that build up masses of limestone are Corallines, Nullipores, Foraminifera, Polyzoa, Crinoids, and molluscs.

(19) Marine limestones have their correlatives formed in freshwater lakes. The organisms that build up fresh-water limestones are mainly molluscs and calcareous algæ.

CHAPTER VII.

CORAL REEFS AND THEIR ORIGIN.

At the present time few questions are of such general interest as the origin of coral reefs, this arising partly from the fascination of their environment and partly from their diversity of form.

The term "coral reef" is commonly used in the conventional sense, and does not imply that corals are the main or only constituent of a reef. Reefs are complex structures, and corals often play a minor part in their construction. Besides corals, Polyzoa, calcareous-algæ, Foraminifera, sponges, echinoderms, and molluscs are important reef organisms.

Coral reefs, using this term in its more general sense, may be divided into:

(*a*) Coral reefs, composed mainly of corals and corallines.

(*b*) Polyzoa reefs, composed mainly of Polyzoa and Foraminifera.

Morphology of Coral Reefs.—The three principal types of coral reefs recognised in existing seas are:

The **Fringing Reef.**
The **Barrier Reef.**
The **Atoll.**

The **Fringing Reef**, as the name implies, is a shore-reef bordering a part of a continent; or wholly, or in part, encircling an island. It usually extends seaward from the shore as a shallow platform of growing coral except the inner edge next the land, which is usually fringed with a narrow belt of dead coral.

Typical examples of fringing reefs occur on the shores of New Caledonia, Isle of Pines, New Hebrides, Sandwich, Solomon and Friendly Islands, etc., in the Pacific; on parts of the coasts of Mozambique and Madagascar in the Indian Ocean; on the African and Arabian coasts of the Red Sea; and around most of the islands in the West Indies in the Atlantic.

The **Barrier Reef** is merely a fringing reef separated from the shore by a wide channel or lagoon. It may lie more or less parallel with a part of the mainland or encircle an island. Good examples of the encircling barrier reef are common in the Pacific and Indian Oceans. They are irregular in shape and seldom form a continuous wall. In places they stand well above the level of the sea, in other places they are submerged or barely awash. If they encircle an island they are always breached by passages that give access to the lagoon. And as an invariable rule where a stream enters the lagoon there is a gap in the reef. The enclosed island may be composed of igneous or other rock, or of old coral reef. The most notable barrier reef in existence is the Great Barrier Reef on the north-east coast of Queensland. It is 1250 miles long, and from 10 to 90 miles wide. Between the outer reef and the mainland there is an inner channel which has a depth varying from 50 to 300 feet. Though the land is festooned with islands and reefs the channel is much used for

navigation. On the ocean side the reef slopes steeply to a depth of 600 fathoms. For great distances its position is only indicated by the break of the sea. It is a great submarine terrace fringing the coast, at each end resting in shallow water, but rising from great depths about the middle. It is covered with from 10 to 60 fathoms of water, and its outer edge is studded all over with steep-sided block-like masses that in many places rise up to low-water level.

The great barrier reefs of New Caledonia are also fine examples of the tremendous industry of the coral polyp. This island consists of a complex of gneiss and schist followed by a vast mass of serpentine associated with Triassic and Cretaceous rocks. It is long and narrow and runs approximately N.W.-S.E. Both shores are fringed with a platform of coral averaging about 10 miles wide. On the outer edge the coral forms a barrier composed of submerged reefs and coral blocks that stand above sea-level.

There is a barrier reef on each coast, and each reef pursues its course far beyond the ends of the island. The barrier reef on the north-east coast extends from the south of the Isle of Pines to the north of the Belep Islands, a distance of 330 miles, while the barrier reef on the south-west coast begins on the south, 30 miles beyond the end of the mainland, and extends north-west to the Belep Islands, a distance of 310 miles.

The most striking form of coral reef is the **Atoll**, which is a more or less irregular ring of reef enclosing a lagoon, without a central island. The depth of the lagoon varies from 30 to 50 fathoms ; and the floor is usually flat and the outer slope steep.

Soundings show that the outer slope of atolls is steeper than that of volcanic cones, this doubtless arising from the rate of upward growth being faster than the outward.

Atolls vary in size from less than a mile to 90 miles in diameter. Frequently small atolls rise from a submerged platform of coral as in the Maldives. Completely closed atolls are rare. Of these Clipperton Atoll [1] in the North Pacific is one of the best known. As a rule atolls are breached by one or more boat channels that usually lie on the leeward side.

Distribution of Coral Reefs.—Besides the Great Barrier Reef of Queensland and the barrier reefs of New Caledonia, coral reefs almost without number are scattered throughout the Indian and Pacific Oceans. Coral development is greater in the Pacific than in the other seas on account of the greater expanse of that ocean lying within the tropics.

Over 200 atolls, the majority of them only a few feet above sea-level, are scattered throughout the Indian and South Pacific Oceans. The principal atolls in the Indian Ocean are the Laccadive and Maldive Islands, the Chagos Bank, and the Saya de Malha, which form a stretch of submerged land between India and the north of Madagascar. It is not inconceivable that such a group of islands, before they were submerged, may have formed a continuous land connection from Mozambique to the Malabar coast of India. Such a connection would help us to understand the presence of an African element in the Indian land fauna.

In the South Pacific the principal atolls are the Low Archipelago, Gilbert Group, Marshall, and Carolina Islands.

Coral reefs of great extent exist on both shores of the Red Sea. They extend down the Zanzibar coast and the coast of Mozambique, and surround the Mauritius. If subsidence of the east coast of Africa were to take place, the latter would form barrier reefs running parallel with the present coast-line.

[1] Wharton, *Quart. Jour. Geol. Soc.*, vol. liv., 1898, p. 228.

The coral reefs of the coast of Florida are typical examples of the fringing reefs that occur on a shallow continental platform. From 5 to 30 miles off the south of the Florida coast there are a number of small islands or "Keys" composed of dead coral and sand.

Materials and Structure of Coral Reef.—On submarine coral platforms the coral polyps grow in irregular colonies that spread out in great mushroom-shaped forms, varying from a few feet to 40 or 50 feet high and from a few feet to many yards in width. The spaces or caverns between the coral mushrooms are the resting-places of coral sand and jagged masses of dead coral. They are inhabited by many molluscs, echinoderms, and fish.

The most important builders of modern reefs are the branching *Madrepores*, *Pocilloporas*, and *Porites*, and the heads of *Astræans* and *Mæandrinas*. Of the hydrozoans, *Millepora* is always abundant, being as a rule represented by the massive *M. complanata*, and the branching *M. alcicornis*. Besides corals many species of nullipores are present and, as at Christmas Island, Fiji, and Funafuti, are often more important than the corals themselves. On all reefs a prominent part in the structure is taken by calcareous algæ, *Foraminifera*, *Echinodermata*, *Polyzoa*, molluscs, and other organisms.

Living corals abound within some of the larger atolls, among them some not found on the outer edge of the reefs. These include the free corals, or those attached by such slender stems that they could not maintain themselves in the strong surf of the open sea.

An abundance of *Madrepora loriceps* and of the vividly coloured branching calcareous algæ *Lithothamnium* as a rule characterises the leeward portion of atolls; while the hydrocoralline *Millepora alcicornis* is conspicuously absent.

Next to *Lithothamnium* (calcite), the branching nullipore *Halimeda* (aragonite) abounds on the reefs, both on the ocean slopes and in the lagoons, and perhaps the great portion of the sand consists of Halimeda fragments mixed with Foraminifera, broken Echinodermata, and shells.

In the upper 180 feet of the Funafuti boring,[1] about one-fifth of the organisms were corals, the remainder consisting of calcareous algæ,[2] foraminifera, etc. Lower down the corals formed a larger proportion of the rock. From top to bottom the same organisms occur, sometimes Foraminifera, sometimes corals predominating.

Rate of Coral Growth.—Investigation has shown that coral growth is relatively rapid. In normal conditions reefs can grow upward at the rate of from 88 to 146 feet in 1000 years.[3] According to Sluiter, a young reef at the Black Cliff of Krakatoa grew a thickness of 8 inches in 5 years, equal to a rate of 140 feet in 1000 years.[4]

THE ORIGIN OF CORAL REEFS.

In the investigation of the origin of coral reefs it should always be borne in mind that the life-work of the tiny polyp is not to create mysteries for the puzzlement of geologists, but simply to live and multiply. In the pursuit of its normal work the coral polyp has always been the greatest builder on the globe. At all times it shows an aggressive readiness to build wherever the

[1] "The Atoll of Funafuti," *Royal Society*, London, 1904, pp. 333–334.

[2] The importance of the part played by calcareous algæ at certain geological horizons has been demonstrated by Professor E. J. Garwood, *Geol. Mag.*, Nov. and Dec. 1913.

[3] J. S. Gardiner, *The Fauna and Geography of the Maldive and Laccadive Archipelagoes*, Cambridge, England, 1903, p. 333.

[4] C. P. Sluiter, *Natuurkundig Tydschr. v. Nedert. Indië*, vol. xlix., 1889, p. 375.

necessary conditions prevail. Briefly summarised the essential conditions are:

1. A tropical sea with a temperature ranging between 73° F. and 84° F., and not falling below 68° F.
2. Free access to the ocean currents so as to ensure a plentiful supply of food and maintain the proper degree of salinity.
3. A sea-floor, shelf or submerged bank covered with a sheet of water not more than 30 fathoms deep.
4. Freedom from sea-borne land sediments.

If only one of these conditions is wanting the rock-building coral polyp is unable to establish itself.

The natural habitat of the coral polyp is the shallow tropical sea; and since the shallow-water condition for the most part exists as a narrow zone around the dry land, it is there that coral reefs abound.

Wherever the coral polyp finds a suitable platform, it begins reef-building. If the platform slopes seaward, the talus of broken coral on the outer edge enables the reef to grow seaward. In this way we find reef-building going on in what was originally water too deep for normal coral-growth.

A coral reef near the shore forms what is called a *fringing reef.* If the form of the rock platform on which the reef is growing is such as to permit the outward progress of the coral reef for a considerable distance from the land, we get the typical *barrier reef.*

During storms, blocks of coral are torn from the outer edge of the reef and piled up above the zone of living coral. Coral and other detritus gather around these tumbled blocks. In this way the outer rim of the reef becomes raised above the level of the sea, or high enough to form a submerged reef against which the swell of the sea breaks with great force, forming the line of broken water that usually marks the seaward edge.

The Barrier Reef may precede the Fringing Reef.—In the Pacific and Indian Oceans there are hundreds of coral-limestone islands of low-relief encircled by fringing reefs. It does not seem unreasonable to believe that if these islands were to sink slowly, the fringing reefs would grow upward and eventually become barrier reefs, as postulated by Darwin and Dana, provided the rate of submergence did not exceed the maximum coral-growth. But the existence of these coral islands is a proof of uplift. There is no direct evidence that barrier reefs started their career as fringing reefs, though in the case of islands of low-relief they may have done so as a consequence of subsidence.

The field-study of coral reefs suggests the view that in certain conditions the barrier reef may have preceded the fringing reef.

It is inconceivable that any coral reef could begin its existence close to the shore of a tropical island of high-relief. Such a land-surface would be drained by streams that during the torrential rains of the wet season would discharge a large quantity of detritus into the sea. In such conditions no fringing reef could exist. But if subsidence began, the stream-borne detritus would not be spread so far seaward, and given the proper depth, coral-growth might easily begin on the outer part of the detrital platform, and by landward growth eventually form a fringing reef.

During progressive submergence, the zone of sedimentation would advance landward; and as the coast became embayed, by the advancing sea, valley-deltas would also be formed.

Coral growth could not take place where land sediments were being deposited, but it might conceivably advance landward, keeping pace with the retreating

zone of deposition, though separated from it by a neutral zone. In cases where the surface-relief became low, as the result of progressive subsidence and subaerial denudation, the deposition of land detritus would almost cease, or become so meagre that the coral-growth might easily advance close enough to the island to form a fringing reef. If the subsidence continued, this reef might grow upward and eventually form an atoll.

So far we have only discussed coral-growth on a stationary or sinking floor. It now remains to consider the probable effect of uplift, starting as before with a platform built up around the shore by the deposition of detritus arising from the dissection of the land. By progressive uplift the seaward part of the platform would in time rise up to the station of coral-growth, while the landward side of the lagoon would become dry land. In this case uplift would lead to the outward growth of the reef, this being accompanied by recession from the shore of the living coral (fig. 44). If the uplift were accomplished by sudden jolts, instead of gradual uplift, we should get a raised coral platform around the coast and a detrital platform lying to seaward, ready for the establishment of new coral-growth.

At the Isle of Pines a central core of serpentine is surrounded by a platform of coral-limestone—a raised fringing reef—varying from half a mile to four miles in width, and sloping from 40 feet high at the sea-front to 100 feet high along the landward edge. Along the shore the coral-growth has built a new fringing reef many miles wide. If another upward jolt were to take place there would be two raised platforms or terraces of coral-limestone

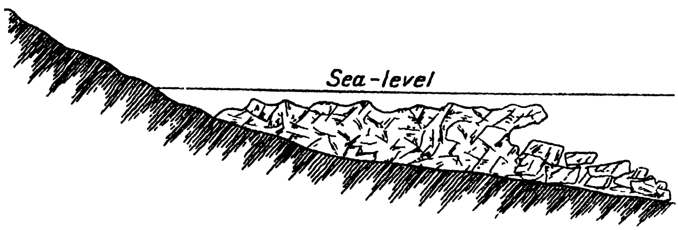


FIG. 44.—Showing growth of coral reef on stationary or slowly rising sea-floor.

around the island, and a new platform of coral-growth would begin to form on the newly raised sea-floor. It is obvious that if the seaward slope of the continental shelf were steep, the rate of outward growth arising from uplift would be slow. On a gentle slope it might be relatively rapid.

The vitality of the coral polyp is remarkable. During the seasonal cyclonic storms, the outer edge of the reefs is battered by the tremendous force of the waves, and broken into small fragments and large blocks, many of which are piled pellmell on top of the living coral in the form of an irregular mound. For many hours after the cyclone has spent its force the outer edge of the reef is clearly outlined by a narrow ring of water heavily charged with coral-mud derived from the pounding of the coral-blocks upon one another. Cyclonic storms arise with uncanny suddenness. And at their height the sea works itself into an astonishing paroxysm of fury, the full brunt of which is directed against the outer reef. The spreading umbrellas are broken, and jagged masses of coral lie everywhere. The wreck of the reef seems beyond repair. In a few days the water clears, and almost at once the coral builders begin the work of reconstruction. The polyps, though easily destroyed by contact with terrigenous sediments, seem to be able to dispose of the coral-mud produced by cyclonic storms. The latter is soluble, the former insoluble, and herein may possibly lie the explanation of what at first sight seems to be a curious paradox. The old polyps are rejuvenated and fresh larvæ start new colonies. Coral polyps as well as the reef-building nullipores do not hesitate to establish themselves on any stationary object that may present itself as a suitable foundation on which to start building.

From the foregoing it is obvious that a coral reef may grow on a stationary, a sinking, or a rising sea-floor. Coral reefs are seen growing around hundreds of islands in the tropical seas on platforms that seem to be stationary, judged by the measure of man's occupation. Borings at Funafuti conducted under the supervision of Professor David have proved that considerable subsidence has taken place in the Ellice group, and the occurrence of raised coral reefs on many of the islands in the Pacific Ocean is a proof of comparatively recent uplift. In the Fiji group raised coral reefs are common, and some occur at a great elevation. The raised coral-limestone in the island of Vatu Vara rises to a maximum height of 1030 feet

above the sea.[1] Along the north coast of New Guinea upraised coral reefs occur at all elevations, from only a few feet above the water up to 2000 feet above sea-level.[2]

According to Dr. T. W. Vaughan, the age of the uplifted limestone of Fiji is Pleistocene or Recent.

The raised platform of coral-limestone that completely surrounds the Isle of Pines is perhaps the best example of a raised fringing reef in the Pacific. It is composed of massive and branching corals, nullipores, Foraminifera, echinoderms, and molluscs, all belonging to living species. Everywhere throughout the limestone coral-sand is abundant. Generally the rock is only partially consolidated. On the coast at Gadji, and in the Bay of Upi, north of Kutomo, there is a fine group of coral-limestone stacks, ranging from 35 to 60 feet high. At water-level these stacks have been deeply undercut by the mechanical and chemical wear of the sea, and some have fallen over through this cause. On the western shore of the Bay of Upi, there are four similar limestone stacks rising from a raised platform about 10 feet above present sea-level.

Everywhere in the Isle of Pines the surface of the limestone platform is scored with chasms and gorges formed by the streams that drain the central serpentine plateau.

At Omangi, near the junction of the serpentine and limestone, the latter has been worn into high cliffs through which large caves have been tunnelled by the streams descending from the central plateau. The largest cave is 40 feet high, and in places 25 yards wide. Its spacious galleries are a striking example of the tremendous amount of erosion that may be accomplished by rain water and small streams in a relatively short interval of time. At the utmost the age of the limestone platform cannot be older than the latest Pleistocene. The floor of the largest cave at Omangi has been cut down from 2 to 6 feet into the underlying serpentine. For a distance of about 80 yards the stream runs in a channel excavated in the bed rock; and for this distance there is exposed on the walls of the cave a good section of the serpentine platform on which the old coral reef rests. The surface of the serpentine, as there exposed, is even, and slopes gently towards the sea. It presents all the features of a wave-cut plane of marine erosion.[3]

Origin of Atolls—Darwin's Hypothesis.

The earliest European navigators in the Pacific believed that atolls owed their existence to the growth of coral reefs around the craters of submarine volcanoes. Later investigation showed that though this explanation might possibly be true in some cases, as at Totoya and Thombia in the Fiji group, it was inadequate for general application. During his memorable voyage in the *Beagle*, Darwin visited South America, the Pacific and Indian Oceans, Australia and New Zealand, and as the result of his investigations formulated his well-known theory of coral-building on a sinking floor, which was for a time generally accepted.

According to Darwin's view, fringing reefs, barrier reefs, and atolls are three successive stages of coral growth on a slowly sinking sea-floor, the growth of the reef being just able to keep pace with the subsidence.[4] He believed that the reef grew upward, and outward on the talus slope of its own debris, the most vigorous growth being on the outside. As a starting-point he conceived an island surrounded with a fringing reef (fig. 45).

During progressive sinking the size of the island became smaller and smaller, and as the corals still grew on the original site, the distance of the reef from the shore became more and more. At first the reef was separated from the

[1] Wilbur G. Foye, "The Geology of the Fiji Islands," *Proc. Nat. Acad. of Sci.*, vol. iii. pp. 305–310, April, 1917.

[2] A. Gibb-Maitland in *Geology and Palæontology of Queensland and New Guinea*, by R. L. Jack and R. Etheridge, Jun., Brisbane, 1892, p. 684.

[3] In 1917–18 the author made a field study of coral reefs on both coasts of New Caledonia, and at the Isle of Pines, Kutomo, Cocos, and neighbouring islands. In 1922 he examined Fanning Island.

[4] C. Darwin, "On Certain Areas of Elevation and Subsidence in the Pacific and Indian Oceans as deduced from the study of Coral Formation," *Proc. Geol. Soc. London*, vol. ii., 1837, pp. 552–554.

slowly disappearing island by a channel or lagoon. Eventually the whole island became submerged beneath the sea, and all that remained was an

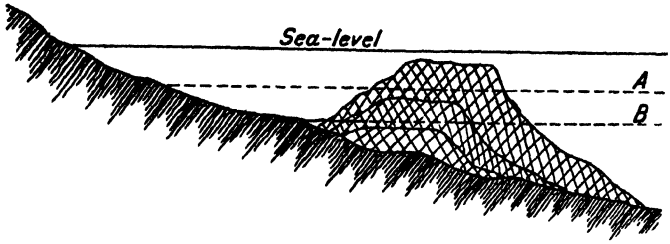


FIG. 45.—Showing formation of Barrier Reef during subsidence according to Darwin's view. *A* and *B* are old shore-lines.

irregular ring of coral reef, enclosing a shallow lagoon. This is the typical atoll (fig. 46).

The borings at Funafuti [1] proved the existence of coral rock at a depth of 1114 feet below sea-level. Here we have conclusive evidence of subsidence amounting to not less than 800 feet since the foundations of the existing reefs were formed.

On the other hand, the occurrence of recent coral reefs that have been raised many hundreds of feet above sea-level proves that the simple explanation of Darwin does not satisfy

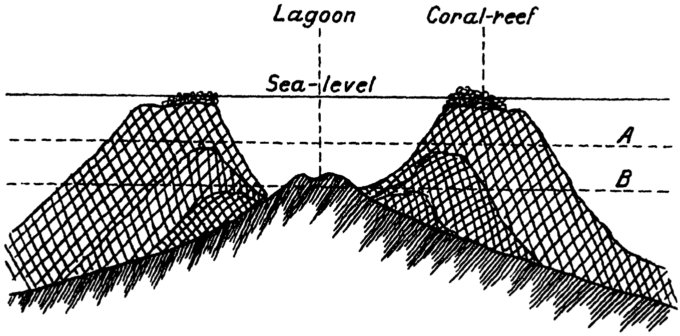


FIG. 46.—Showing progressive stages in formation of *atoll* according to Darwin's view. *A* and *B*, former levels of sea.

all the facts. It is evident that while subsidence was in progress in some areas, uplift was taking place in others.

A consequence of subsidence overlooked by Darwin was the circumstance that an island would not only diminish in size but also acquire a more or less embayed shore line as the result of the invasion of its previously eroded valleys by arms of the sea. This omission was remedied by Professor Dana,[2] who recognised that the partial submergence of a dissected land-surface must produce coastal embayments like that around the coasts of New Caledonia and Tahiti.

Murray's Hypothesis of Coral-Reef Formation.

As the result of his observations during the voyage of the *Challenger*, Sir John Murray became satisfied of the inadequacy of Darwin's theory, and put forward a new view in accordance with which he supposed that coral reefs and atolls had been built upward from submarine banks mainly composed of loose volcanic material. These banks had, he thought, been reduced to a platform

[1] *The Atoll of Funafuti*, Royal Society, London, 1904, pp. 177–180; also W. J. Sollas, *The Age of the Earth*, London, 1905.

[2] J. D. Dana, *Corals and Coral Islands*, 2nd ed., New York, 1879.

by the lower limit of wave-action, supposed to be about 30 fathoms, which is approximately the lower limit of coral-growth. Murray explained the existence of the shallow lagoons within the atolls by solution of the less actively growing or dead coral on the inner side of the reef.[1]

Rear-Admiral W. J. L. Wharton[2] did not consider this solution necessary and proposed a modification of Murray's theory. He suggested that after the complete truncation of the submerged bank, a coral reef grew on the outer edge thereby forming an atoll.

It is almost certain that if an island is subjected to prolonged subaerial and marine erosion it will be eventually reduced to a submerged platform. Even if the land be stationary the depth of water covering it may be increased by the scour and drag of the rocky detritus lying on its surface, or torn from its edge by wave-action and storms. On such a platform the coral polyp would find a good foundation for reef-building.

If a submarine volcano piled up a cone of loose ash, the cone would be similarly truncated.

In 1901–2 a submarine eruption occurred midway between the island of Epi and Tongoa in the New Hebrides group. The eruption took place on a submerged bank where the depth of water before the outburst was about four fathoms. Volcanic activity lasted for nine months, and in that time the ash was piled up so as to form an island about three-quarters of an acre in extent and about 12 feet above sea-level. To claim possession some natives planted cocoanut trees on the newly formed island; but the first hurricane washed the island away, and all that now remains of it is a submerged bank on which the sea breaks in ordinary weather. The bank is now covered with a thin sheet of growing coral. If the bank remains stationary or sinks at a rate less than the growth of the coral, we shall eventually get an atoll.

The question of coral reef origin is essentially the problem of the genesis of the platform on which the coral reefs have grown. The character of the foundation underlying existing coral reefs can seldom be ascertained by direct observation. The exposure of the serpentine platform in the Omangi grotto at the Isle of Pines to which reference has already been made is exceptional. A study of the platforms on which Cainozoic or other coral reefs have grown should throw valuable light on the conditions that accompany the growth of coral reefs.

Coral Reefs and Glacial Control.

This hypothesis implies that fringing reefs, barrier reefs, and atolls are shallow crowns recently built up on Pleistocene wave-cut platforms. It postulates that during the Pleistocene Period the level of the oceans was lowered by the withdrawal of water for the formation of the great ice-caps. With the advent of warmer conditions the ice-caps gradually diminished in size and the level of the sea rose slowly higher and higher. On the submerged platforms coral larvæ established themselves, and as the submergence progressed, the reefs grew upwards and inwards. This view of coral-reef formation is not new. It was outlined by Mr. Belt[3] in 1874, and discussed by Mr. Upham[4] in 1878.

In 1882 Professor Penck[5] estimated that the Pleistocene glaciation in the Northern Hemisphere alone sunk the general level of the sea 216 feet below its present level, assuming that the Antarctic ice-cap was then as large as it is now. If that ice-cap were then non-existent, the Pleistocene sea-level would have been about 162·5 feet below its present level. In 1894[6] Penck postulated that with a general lowering of sea-level by the formation of the ice-caps many banks would become subject to wave abrasion.

In 1896, Penck in a lecture in Vienna, in which he reviewed the different coral-reef theories,

[1] *Proc. Roy. Soc. Edin.*, vol. x., 1880, p. 505; "*Challenger*" *Report, Narrative*, vol. i. p. 781.

[2] *Nature*, vol. iv., 1897, pp. 390–393.

[3] T. Belt, *Quart. Jour. Sci.*, vol. ii., 1874, p. 450.

[4] W. Upham, "Geology of New Hampshire," *Concord*, vol. iii., part 3, 1878, p. 18.

[5] A. Penck, *Jahrbuch Geog. Ges.*, München, 1882.

[6] A. Penck, *Morphologie der Erdoberfläche*, Stuttgart, vol. ii., 1894, p. 660.

announced his complete acceptance of Darwin's theory, and made no reference to the Glacial Control hypothesis, which he appears to have abandoned.[1]

In 1910, Professor R. A. Daly [2] reviewed the Glacial Control theory. In 1915 he elaborated his views [3] and succeeded in showing that changes of sea-level arising from the formation of ice-caps was competent to explain the erosion of the platforms and submerged banks on which many atolls have been built. Like Admiral Wharton and Dr. Vaughan, he recognises that the origin of coral reefs is essentially the problem of the origin of the platforms on which the coral reefs have grown.

As shown by Lord Kelvin,[4] Woodward,[5] and others, the lowering of the sea-surface by the gravitative attraction of an ice-cap like that covering the northern part of North America in Pleistocene time may be considerable. Daly postulates that the formation of the Pleistocene ice sheets, and the gravitative attraction of the ice masses would together cause a lowering of sea-level amounting to 200 feet or more in the tropical oceans. At the same time the average temperature of the oceans would also tend to fall so that in seas where the temperature ranged only a few degrees above the lowest limit of coral growth, *i.e.* 68° F., the reef-builders would be killed.

According to his view the reefs were then attacked by the waves and cut down to smooth platforms, a little below the sea-level of the time. Afterwards, with the melting of the continental glaciers, rise of sea-level, and advent of a milder climate, coral larvæ established themselves on the outer rim of the platforms. The new reefs grew upward and in time enclosed a lagoon.

Daly rightly concludes that the flat floor of atolls supports his view of platform abrasion arising from glacial control, and quotes Admiral Wharton,[6] an authority on oceanic bathometry, who, in a discussion of coral-reef origin, writes: "I have no hesitation in saying that a flat floor is an invariable characteristic of a large atoll, and I cannot find his (Darwin's) deeply concave surface in any large atoll. On the contrary, a flat surface is found in all of these, whether the rim be above or below the surface."

Daly postulates that if the reef platforms have been finally prepared by wave and current action, the similar platforms at about the same depth should be continuous outside the coral seas. He contends that large-scale charts give proof in plenty of the existence of such benches, a notable example being the platform from which the Great Barrier Reef of Australia rises. The Great Barrier ends about the 24th parallel of South latitude, but the shelf continues far beyond to the southward.

Professor Foye,[7] who made a field study of the coral reefs of the Fiji group in 1915, concludes that the modern reefs of Fiji and elsewhere are growing on basements that are antecedent to the reefs. He believes that Pleistocene wave-cut benches exist very generally throughout the coral seas, though the platforms in Fiji are much more modern.

He concludes that the development of the modern coral reefs of Fiji does not fully support Darwin's theory, since their history is not expressed by the simple succession of fringing reef, barrier reef, and atoll. The history of the older elevated limestones more nearly coincides with Darwin's theory of subsidence than does the history of the modern reefs.

Glacial periods have been recurrent in past geological times, hence successive lowerings of sea-level must be admitted. But the possible effect of contemporaneous diastrophic movement arising from the load imposed by the gathering ice-caps is a question that has not been considered by the writers who support the theory of Glacial Control.

General Review.

From the foregoing we find that coral reefs may grow on a stationary, sinking, or rising sea-floor.

On a stationary floor the growth will be mainly seawards, the talus of broken coral affording a foundation for the outgrowing reef.

[1] R. A. Daly, "Glacial Control Theory of Coral Reefs," *Proc. Amer. Acad. Arts and Sciences*, vol. 'i., No. 4, Nov. 1915, p. 165.

[2] R. A. Daly, *Amer. Jour. Sci.*, vol. xxx., 1910, pp. 297–308.

[3] R. A. Daly, *Proc. Amer. Acad. Arts and Sciences*, vol. li., No. 4, Nov. 1915, pp. 158–251.

[4] *Philosophical Magazine*, vol. xxxi., 1866, p. 305.

[5] R. S. Woodward, *Bull. 48, U.S. Geol. Sur.*, 1888.

[6] W. J. L. Wharton, *Nature*, vol. lv., 1897, p. 390.

[7] Wilbur Garland Foye, "Geological Observations in Fiji," *Proc. Amer. Acad. Arts and Sciences*, vol. liv., No. 1, Sept. 1918.

On a sinking sea-floor three conditions may exist:

(1) The rate of sinking may be less than the rate of coral-growth.
(2) The rate of sinking may be equal to the rate of coral-growth.
(3) The rate of sinking may be greater than the rate of coral-growth.

If the rate of sinking is less than the rate of coral-growth then the reef-building will be upward and outward, the outward growth being relatively rapid if the slope of the sea-floor is gentle.

If the rate of sinking is equal to the rate of coral-growth the reef will grow upward and outward, and in this case the rate of outward growth will depend as before on the slope of the sea-floor.

In both these cases the downward movement will tend to diminish the size of the island. If the shore-line is steep the diminution may be small, but arms of the sea will reach into the valleys, shore-line deposition will take place, and valley-deltas will be formed. If the surface relief of the land is high, or even moderate, and the rainfall plentiful, the detritus of subaerial denudation will be spread in a wide zone on the sea-floor around the land, the width of this zone depending on the slope of the sea-floor. If the slope is steep, as is often the case near land of high relief, the depth of the water outside the zone of sedimentation may be too deep to permit the coral larvæ to establish themselves. But if the slope is gentle, as it may be opposite a land-surface of moderate relief, though the zone of sedimentation will be relatively wide, the depth of water may not exceed the limit of coral-growth.

The progressive downward movement will cause the zone of sedimentation to advance landward, and on the newly formed detritus platform, now outside the influence of shore deposits, the coral larvæ may start building. In this case the coral-growth will be mainly upward and landward; and in the off-shore reef thus formed we have the beginning of a barrier reef. In consequence of the progressive sinking and inward growth, accompanied by the landward recession of the zone of deposition, we will in time get the typical fringing reef. If the downward movement continues till the island became wholly submerged, we will get the typical atoll.

According to the views of Darwin and Murray, the successive stages of coral-growth are first the fringing reef followed by the barrier reef and atoll. According to the writer's view the progressive stages would be first the barrier reef, then the fringing-reef, and atoll.

If a submarine bank is uplifted to the 30-fathom line in a tropical sea, the coral polyp will be certain to establish itself on its surface and in time form a coral platform.

If the sea-floor is stationary, the outer edge of this platform will grow upward at a greater rate than the middle and thus in time we may get an atoll, without the intermediate stages of fringing and barrier reefs. Or if the crater of a submarine volcano is raised to the coral-building station, we will in like manner get the typical atoll.

Half-way between the mainland of New Caledonia and the Isle of Pines there is a low coral island surrounded with a submerged barrier reef on which the sea breaks only at low-water. The reef lies about 100 yards from the island, which is about 15 feet high and composed entirely of coral-limestone. Here we have an example of a submerged coral reef that has been uplifted. Coral-growth continued around its shore forming a fringing reef, and then subsidence began. By the upward growth of the fringing reef there has been built up the existing submerged barrier reef. It is evident that the island has been considerably reduced in altitude by atmospheric solution.

There are many limestone islands encircled with barrier reefs in the Pacific Ocean, and of these Ongea and Fulanga[1] in the Fiji group may be taken as typical. The origin of these islands is still in doubt. They may be elevated atolls or Pre-Pleistocene coral reefs that were elevated and then partially submerged by negative movement in recent times.

The theory of Glacial Control as presented by Professor Daly (1915) is a worthy rival of the theories of Darwin and Murray, though it still leaves some problems unsolved. As far back as 1834, Dr Jamieson[2] of Elgin, Scotland, suggested that the overloading of the polar regions with ice would tend to cause crustal deformation. A question raised by the theory of Glacial Control is the probable diastrophic effect of the piling up of the Pleistocene ice-caps; and till this has been solved it will not be known whether the recession of the sea arising from the growth of the ice-caps was increased or diminished. If the effect increased the emergence of islands of modern relief, we should expect the early part of the Pleistocene to be characterised by valley erosion and the formation of near-shore detrital platforms. On the submergence following the period of maximum refrigeration, the mouths of the valleys would be drowned and sediments piled up near the shore with landward overlap on the first formed detrital shelf. If, on the other hand, the diastrophic movement was negative and equal to the positive effect produced by the refrigeration there would be no recession of the sea, and instead of valley erosion we should get a condition favouring inshore deposition and delta-forming. In this case, with the advent of warmer conditions, reef-building would begin off-shore. And submerged banks and islands just awash would not be abraded into the platforms postulated by Daly, though it is probable that reef-building would begin on or around them.

For some cause that is difficult to explain the Pacific basin in certain areas is divided into groups of relatively small crustal blocks, some of which are sinking while others are rising. Even in the same group some show evidence of Pleistocene or Recent uplift and others of subsidence. In these circumstances it is improbable that any one hypothesis will explain all the conditions in which coral-building may take place. Given a tropical sea and a shallow bank, or a shore free from the deposition of terrigenous matter, the coral polyp will build a reef, whether the sea-floor is stationary, sinking, or rising. The form of the reef will be determined by the local conditions. In New Caledonia the barrier-reef in places spreads inshore and becomes a fringing reef. In some islands fringing reefs are encircled by barrier reefs, and in others, coral islands are enclosed in barrier reefs.

Ancient Coral Reefs.

Limestones composed wholly or mainly of corals and other calcareous organisms occur in all the geological periods from the Ordovician upwards. Some of these probably represent ancient coral reefs; that is, they are made up of corals that grew in place, the interstices being filled with broken coral, coral-mud, and the remains of calcareous algæ in which are embedded molluscs, Foraminifera, and Echinoderms. Coral-rock is liable to undergo alteration as the result of water percolating through it, whereby the original structure is more or less obliterated, the rock being converted into a compact or crystalline limestone. And this secondary change may take place in a relatively short time:

At the Isle of Pines, the raised coral reef that surrounds the island, though composed of corals, molluscs, etc., that are still living in the adjacent seas, has become in many places changed into a compact semi-crystalline limestone. Many of the raised coral-reefs of Fiji, Sandwich Islands, and elsewhere, none of which are probably older than the Pliocene, have been altered in the same way.

Dupont described fossil-atolls in the Devonian calcareous rock of Belgium; and von Richthofen (1860), in his account of the geology of the St. Cassian district in the South Tyrol, expressed the opinion that the South Tyrol dolomites were ancient coral reefs, a view afterwards confirmed by Mojsisovics (*The Dolomite Reefs of South Tyrol*, 1879), though previously challenged by

[1] J. S. Gardiner, "Coral Reefs of Funafuti, Rotuma, and Fiji," *Proc. Camb. Phil. Soc.*, vol. ix., part 8, 1898, pp. 457 and 471.

[2] T. F. Jamieson, *Geol. Mag.*, vol. xxi., 1865, p. 178; vol. ix., 1882, p. 461.

Gümbel (1873). In 1894 Miss M. Ogilvie adversely criticised the coral-reef origin of the Tyrol dolomites, but like Gümbel failed to make due allowance for the complex structure of coral reefs.

Some uncertainty still exists as to the fossil-atolls described by Dupont. The ring-like arrangement of the limestones may be the result of denudation acting on a series of folded strata that contain beds of coralline limestone. Owing to the action of denudation and crustal movements, it can only be in exceptional cases that the original form of any Palæozoic or Mesozoic coral reef can have been preserved so far that it is now possible to distinguish it as a fringing reef, barrier reef, or atoll. In the Cainozoic rocks denudation has often been so relatively slight that the original form of the reef may admit of determination.

The coralline limestones of the Ordovician and Silurian are largely, often mainly, made up of the remains of Stromatoporoids, a large group of calcareous Hydrozoa.

While a vast development of coralline limestones exists in the Carboniferous, no true coral limestones have been identified in the Permian, which was, as we shall afterwards find, a period of widespread glaciation.

The Palæozoic or tetracoralline (rugose) type of stony cup-shaped and astræan corals predominate in the Carboniferous and earlier periods. The hexacorallines of the present day dominate the Mesozoic and Cainozoic.

True coral reefs appear at the close of the Triassic, being abundantly represented in the Eastern Alps, and still more extensively in the Jurassic of Western Europe and Britain. There is a great development of true coral reefs in the early Cretaceous of France and Crimea, and coral reefs were formed in the earlier portion of the Tertiary in Southern Europe, in Egypt, Arabia, and India. In the later Tertiary, coral reefs are not strongly represented except in the warmer parts of Pacific and Indian oceanic areas, where they are still growing vigorously.

CHAPTER VIII.

ROCK-BUILDING.

THE CONSTRUCTION OF SEDIMENTARY ROCKS.

BY far the greatest visible portion of the Earth's crust is composed of sedimentary or aqueous rocks. We will therefore now consider the original constitution of these rocks as resulting from the conditions under which they were formed.

Among the various structures to be considered are *stratification*, *false-bedding*, and *lamination*.

Forms of Bedding.

All fragmentary material derived from the denudation of the land is eventually laid down on the bed of the sea or on the floor of some lake or river, where it is sorted by the action of the water and spread out in layers or beds that are also called *strata*.[1]

The strata or beds, according to the conditions in which they were formed, may be *marine*, *lacustrine*, or *fluviatile*. In other words, the layers of gravels, sand, and mud laid down on the floor of the sea form what are termed *marine* beds ; those deposited in a lake-basin, *lacustrine* beds ; and the deposits laid down in a river-bed, *fluviatile* beds. Deltaic deposits are partly fluviatile and partly marine, and for that reason are sometimes called *fluvio-marine*.

Stratification.—We found in Chapter VI. that the detritus discharged into the sea is *sorted* and *spread out* into three principal zones running nearly parallel with the shore, the coarsest material being deposited nearest the shore, and the finest furthest seaward.

The material in each zone is approximately uniform in size, the sorting or grading into sizes resulting from the operation of the well-known hydraulic principle that *equal particles falling in water offer an equal resistance.* This principle can easily be illustrated by throwing a mixture of coarse sand, fine sand, and silt into a tall glass jar filled with water. The coarse sand, fine sand, and silt will after a little time be found to have settled in three distinct layers, the coarsest being at the bottom because it fell the quickest, with the finest at the top because it settled the slowest (fig. 47).

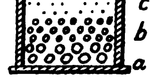


FIG. 47.—Showing sorting action of still water.
(*a*) Coarse sand. (*b*) Fine sand. (*c*) Silt.

The deeper the water into which the mixture is thrown, the more complete will be the separation, and the cleaner the products in each layer.

[1] *Strata*, the plural of *stratum*=a layer or bed.

The separation or sorting just described takes place only in still water, a condition that is seldom or never met with in nature.

Let us now assume that a similar mixture is thrown into the head of a long box-launder or chute through which there is flowing a slow stream of clean water. The flowing water possesses the same sorting action as still water, and we shall again obtain three sorted products; but instead of these being arranged vertically one above another as in our first experiment, they will be spread out in the same plane, the falling particles being deflected in their descent in the direction of the flowing water.

The particles have two motions—a vertical and a horizontal; hence, the more slowly they fall through the water, the greater will be the travel or deflection before they settle on the bottom. And since the heaviest particles fall first and the finest the last, we shall get the coarse sand at the head of the launder, the fine sand in the middle, and the silt at the tail, as shown in fig. 48.

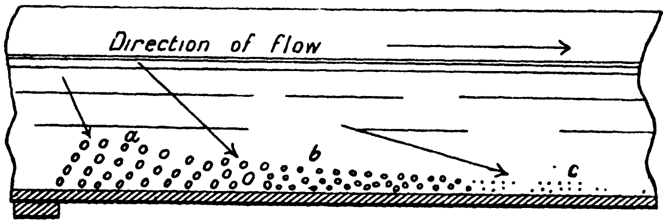


FIG. 48.—Showing sorting and spreading action of moving water.
(a) Coarse sand. (b) Fine sand. (c) Silt.

For the *sorting* and *spreading out* of detrital material we require the water to be in motion, and this condition is always provided in the case of the sea by the daily tides, sea-currents, and the wave motion generated by winds.

Size of Grains.—Metallurgists and engineers have made many attempts to define the various types of rock and mineral particles based on the size of the grains, but up till now no general standard has been adopted.[1] The sizes recognised by many engineers, using sieves made of standardised wire for sizes below 2·0 mm. are:

1.	Very coarse gravel	50·00 to 25·00 mm.
2.	Coarse gravel	25·00 to 15·00 mm.
3.	Medium gravel	15·00 to 5·00 mm.
4.	Fine gravel	5·00 to 2·00 mm.
5.	Very coarse sand	2·00 to 1·25 mm.
6.	Coarse sand	1·25 to 0·65 mm.
7.	Medium sand	0·65 to 0·35 mm.
8.	Fine sand	0·35 to 0·15 mm.
9.	Very fine sand	0·15 to 0·10 mm.
10.	Silt	0·10 to 0·05 mm.
11.	Very fine silt (rock-floor)	0·05 to 0·01 mm.
12.	Clay size	0·005 to 0·0001 mm.

Sands sorted out by moving water usually consist of several grades of size,

[1] Except sieves made of standardised wire are used comparable results cannot be obtained.

one of which will, as a rule, greatly preponderate. The winnowing effected by wind is more perfect than the sorting brought about by water; hence the grades of desert sands and dust are more clearly defined than those of water-borne sediments.

Stratification of Conglomerates.—Conglomerates frequently exhibit no lines of bedding, and when they do these arise from the alternation of layers of coarse and fine material. Thus, bands of sandstone or shale impart a bedded or stratified appearance to the layers of conglomerate lying between them.

Fig. 49 shows a section of a bluff of conglomerate which exhibits no appear-

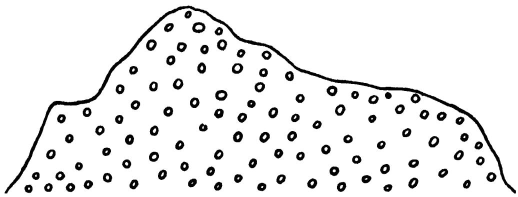


Fig. 49.—Showing conglomerates without bedding.

ance of bedding; but the same conglomerate, when it contains sandstone bands *a-a*, is seen to present a bedded or stratified appearance (fig. 50). Stratification, generally speaking, is produced by a change in the material deposited.

It should be noted that the bands of sandstone that occur in a conglomerate are usually extremely variable in thickness and linear extent. This is what might be looked for where fine material is laid down among coarse, the fine

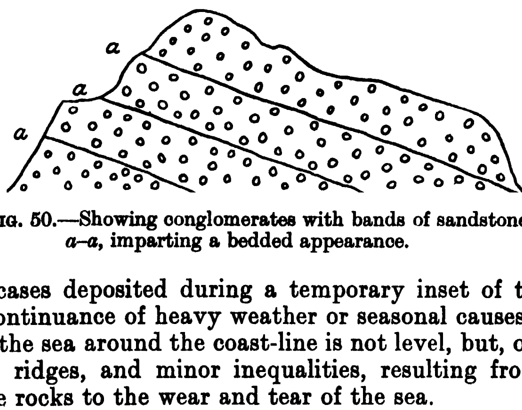


Fig. 50.—Showing conglomerates with bands of sandstone, *a–a*, imparting a bedded appearance.

being in most cases deposited during a temporary inset of the coastal sea-currents by a continuance of heavy weather or seasonal causes.

The floor of the sea around the coast-line is not level, but, on the contrary, full of hollows, ridges, and minor inequalities, resulting from the unequal resistance of the rocks to the wear and tear of the sea.

The first detritus laid down on the uneven floor of the sea will be spread out as a sheet of variable thickness. The tendency of the material will be to fill up the hollows and depressions, in consequence of which the sheet, while gradually tapering from the shore-line seaward, will be thickest in the hollows and thinnest on the ridges. In other words, the first sheet of material will conform to the contour of the floor on which it rests.

The next sheet of detritus will be spread over the first, but the hollows will receive a thicker coating than the other portions of the floor. As layer after layer is laid down, the hollows will be completely filled up; and after that happens, the succeeding layers will be parallel throughout (fig. 51).

On a gently shelving sea-floor, when the level of the land relatively to the sea is stationary, or when the land is rising slowly, the detritus is carried

further and further seaward, with the result that the successive zones of sorted material do not lie vertically above one another, but *overlap* going *seaward*, the upper sheets overlapping the lower as shown in fig. 52. The result of this overlapping is that different grades of material succeed one another in a vertical

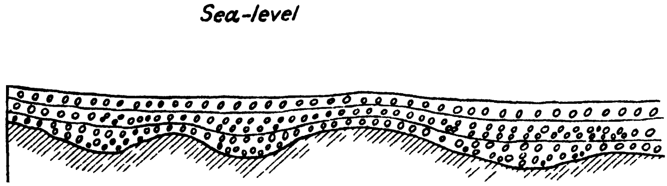


FIG. 51.—Showing parallelism of beds after the hollows in the sea-floor are filled up.

line. Thus a bed or stratum of mud may be followed by a bed of sand, and a bed of sand by one of gravel. This alternation of different grades of material produces, when consolidation takes place, what is known as *stratification*.

Alternations of thin beds of sandstone and thinner beds of slaty shale are

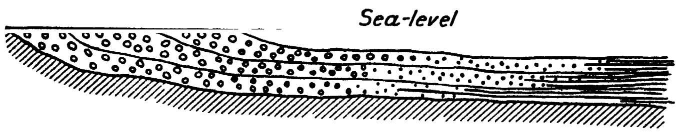


FIG. 52.—Showing seaward overlap as a result of deposition on a stationary or rising sea-floor.

frequently seen among the older rock-formations, and this alternation may persist through a thickness of many thousand feet. In this case the deposition of fine silt or mud on the sands may have been due to small seasonal variations in the velocity of the sea-currents, or to the seasonal changes in the prevailing

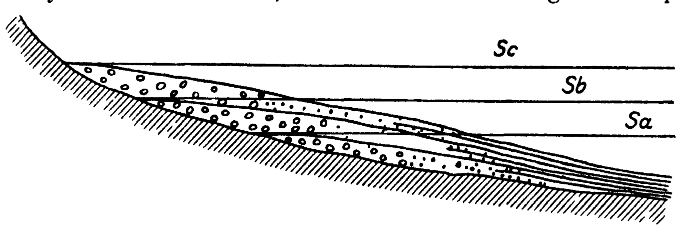


FIG. 53.—Showing landward overlap as the result of deposition of detritus on sinking sea-floor.

Sa, *Sb*, and *Sc* mark successive sea-levels.

winds, exercising an influence on the direction and strength of the currents, or to the varying power of the tides.

Theoretically, a conglomerate which is a shore-line deposit ought to graduate going seaward into a sandstone, and from a sandstone into a mudstone ; but owing to the mixing up of the material through coastal currents and gales at the time of the deposition, this condition is perhaps seldom found to exist in nature.

On a sinking shore-line with an advancing sea, the overlap of the successive layers of detritus laid down on the sea-floor will be on the *landward* side (fig. 53).

Lamination.—When a rock occurs in very thin layers it is said to be *laminated*. The *laminæ* may vary from the hundredth of an inch to an inch thick. A laminated structure is characteristic of rocks composed of silt or mud. The laminæ frequently vary in colour. Thus one lamina may be greyish blue; another greenish grey, yellowish brown, or red. Alternating laminæ of different colours give the rock a ribbon-like appearance when viewed in sectional elevation.

Glacial clays, shales, and slates frequently possess a laminated structure. These are composed of the fine sediments carried by rivers into seas and lakes, being deposited where there is little or no movement in the water, or of muds spread over the floor of estuaries and tidal harbours.

Investigation has shown that the lamination, even when paper-like, is due to minute differences in the size of the particles. The process of deposition of very thin layers is, like stratification, dependent on the principle of *equal falling particles*. Let us assume that a silt-laden river like the Amazon enters the sea with a velocity of one foot per second. It is obvious that the suspended particles will settle on the sea-floor in parallel zones, the coarser silts first and the finest furthest seaward. But if through any cause, such as the daily pulsations of the tides, the velocity of the current is checked, we shall get frequent alternations of normal flow and slack-water, with the obvious result that in any certain zone there will be deposited alternating layers or laminæ of fine and excessively fine silt, laid down one above another. This process of lamination can be seen in operation in all of our mud-filled tidal harbours. In these also near the entrance, muds are deposited in alternating layers, due to the varying power and velocity of the inrushing tides.

Glacial silts laid down in shallow lakes frequently possess a laminated structure. The lamination in this case is due to the daily and seasonal variations in the flood-level of the glacial river. Glacial rivers, particularly in spring and summer, exhibit a daily rise and fall, the maximum rise taking place in the afternoon. The velocity of flow varies with the depth of the water, and in consequence we get at the point of discharge an overlapping of sediments of different grades which, as we have seen, induces the structure termed *lamination*.

Laminated rocks generally split readily in a direction parallel to the plane of the laminæ. The presence of finely comminuted flakes of mica adds greatly to the ease with which the splitting takes place.

The differences in colour frequently met with in laminated rocks are due to slight variations in the composition of the sediments laid down at various times or seasons. A river like the Amazon drains nearly half a continent. Many rock-formations are represented within its watershed. The large tributaries are not always in flood at the same time. Thus one tributary may, when in flood, contribute chalky muds, and another tributary slaty or micaceous silt. In this way the alternation of different-coloured sediments is obtained.

Lamination is thus seen to be merely a minute form of stratification, mainly, but not exclusively, the work of water. The dust ejected from the great fissure-rent during the Tarawera eruption in 1886 was a mixture of various grades of fine material. In many places it settled in thin laminæ, the sorting into uniform grades of equal-falling particles being effected by the winnowing action of the high wind prevailing at the time. The wind did not maintain a steady pressure, but came in powerful blasts, which thus allowed layers of dust of different fineness to settle one after another in the same zone.

The sands forming coastal dunes frequently possess a laminated or banded structure, also due to the varying velocity of the prevailing winds.

The crest of the detritus above *a-b* may be afterwards cut away by the river during floods, forming a new plane of deposition for further sediments (fig. 55).

False-Bedding.—This is a bedding that does not lie parallel to the general bedding plane of the formation in which it occurs. It is frequently found in sands and fine gravels deposited on the bed of the sea, on the floor of a lake, or in the channel of a river; and is frequently a quite local phenomenon.

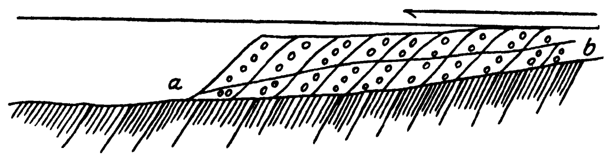


FIG. 54.—Showing formation of false-bedding at head of lake.

False-bedding, also called *current-bedding*, may be frequently seen in process of formation at the head of valley-lakes that are being filled up with river detritus, also in the broad shingle beds of mountain streams and in deltas.

The gravels and sands, as they are discharged into the lake-basin in times of normal flow, are laid down in an inclined position like the material tipped from trucks at the end of a mine-dump (fig. 54). During floods, the river acquires a greater velocity and is thereby enabled to cut away the crest of the detritus previously laid down at the head of the lake (fig. 54, line *a-b*). As the flood slackens, a sheet of detritus is laid over the truncated edges of the

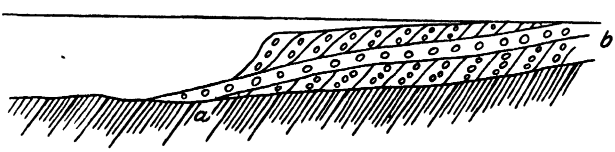


FIG. 55.—Showing false-bedding in lacustrine detritus poured into a lake-basin.

inclined beds *a-b*; and when the flood finally subsides and normal conditions prevail, the fresh material discharged by the river is once more laid down in the now almost still water in an inclined position like the first, and we get the appearance shown in fig. 55.

It should be here noted that the detritus is not carried in suspension, but is rolled along the bottom till it reaches the edge of the *tip*, where it rolls down, at once adjusting itself to the natural angle of rest.

False-bedding is frequently seen in loose river gravels at places where holes have been scoured in the bed, or old shallow channels have been gradually filled up by the tipping process mentioned above. When filled up to the normal flood-plane, the inclined beds tipped into the depression are overspread with sheets of gravel lying parallel to the plane of flow (fig. 56).

False-bedding is also seen in river-gravels laid down in what is termed a *back-water* or elongated eddy in which the current runs in the opposite direction to that of the general flow of the stream.

The false-bedding of estuarine or fluvio-marine sediments is of frequent occurrence. It usually takes place in the same manner as in lacustrine deposits, and is more often seen in sandy beds than in conglomerates.

Wind-blown sands frequently exhibit fine examples of false-bedding. The sand is driven before the wind till it reaches the lee-side of a ridge or edge

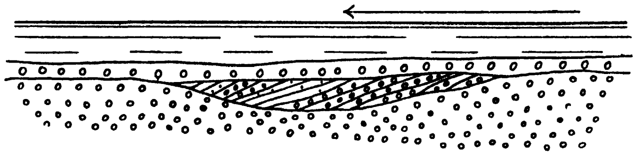


FIG. 56.—Showing false-bedding in river-gravels.

of a declivity where it immediately falls down the sheltered slope, forming layers more or less parallel with the angle of rest, as shown in *A* of fig. 57, in which the direction of the wind is indicated by the arrow.

When the wind blows from the opposite direction, the crests of the inclined layers of sand are liable to be truncated along the line *a-b*. When this happens,

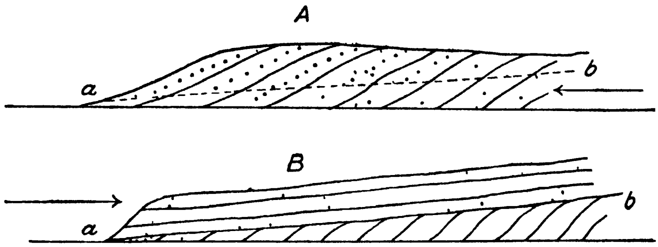


FIG. 57.—Showing false-bedding in wind-blown sands. (For explanation of *a–b* see the text.)

fresh layers of sand are sometimes, but not always, laid down in a nearly horizontal plane, as shown in *B*, fig. 57. It sometimes happens that the wind after truncating the inclined layers begins to build up a new set of layers inclined towards the direction in which the wind is travelling.

Current-laid Stones.—In rivers, and in all currents of water that run con-

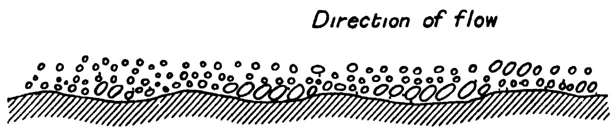


FIG. 58.—Showing arrangement of stones in a river-bed to resist being lifted.

tinually in the same direction, the larger stones, particularly those of a slabby shape, tend to arrange themselves in such a way as to offer the greatest resistance to the water flowing over them (fig. 58). This arrangement can be seen in almost every gravel terrace composed of layers of fine and coarse gravel. It always affords a valuable clue to the gold-miner as to the direction of flow of the ancient river that formed the terrace, thereby enabling him to locate with some degree of certainty the position of the gold-bearing drift.

Surface Markings on Sediments.

From our study of the manner in which sediments are formed on the sea-floor, we are able to deduce two fundamental truths that have an extraordinary importance in connection with the unravelling of the history of the Earth. These truths, which are now recognised as geological axioms, may be expressed as under:

(1) That all mechanically formed sediments are composed of the waste of pre-existing land.
(2) That all marine detrital sediments were laid down marginal to land areas. That is, they are thinogenic.

The only notable exception to this are the deposits of volcanic ash spread over the sea-floor by submarine volcanoes.

Hence, in his endeavour to trace out the geographical distribution of the land and sea at the different stages of the Earth's history, the geologist searches for all the evidences that indicate the former existence of shore-line conditions of deposition.

The most trustworthy and tangible evidences of ancient shore-lines are beds of conglomerate composed of beach-shingle, and rocks containing the remains of marine life that are known to live only in shallow water. These outstanding and indestructible proofs are frequently supplemented by facts that may in themselves appear insignificant, but are not less valuable in affording clues as to conditions of deposition on which special emphasis may be safely laid.

Among these minor proofs are *ripple-marks*, *sun-cracks*, *rain- and hail-prints*, and *animal trails*, all of which have been found in rocks composed of sediments of fine texture.

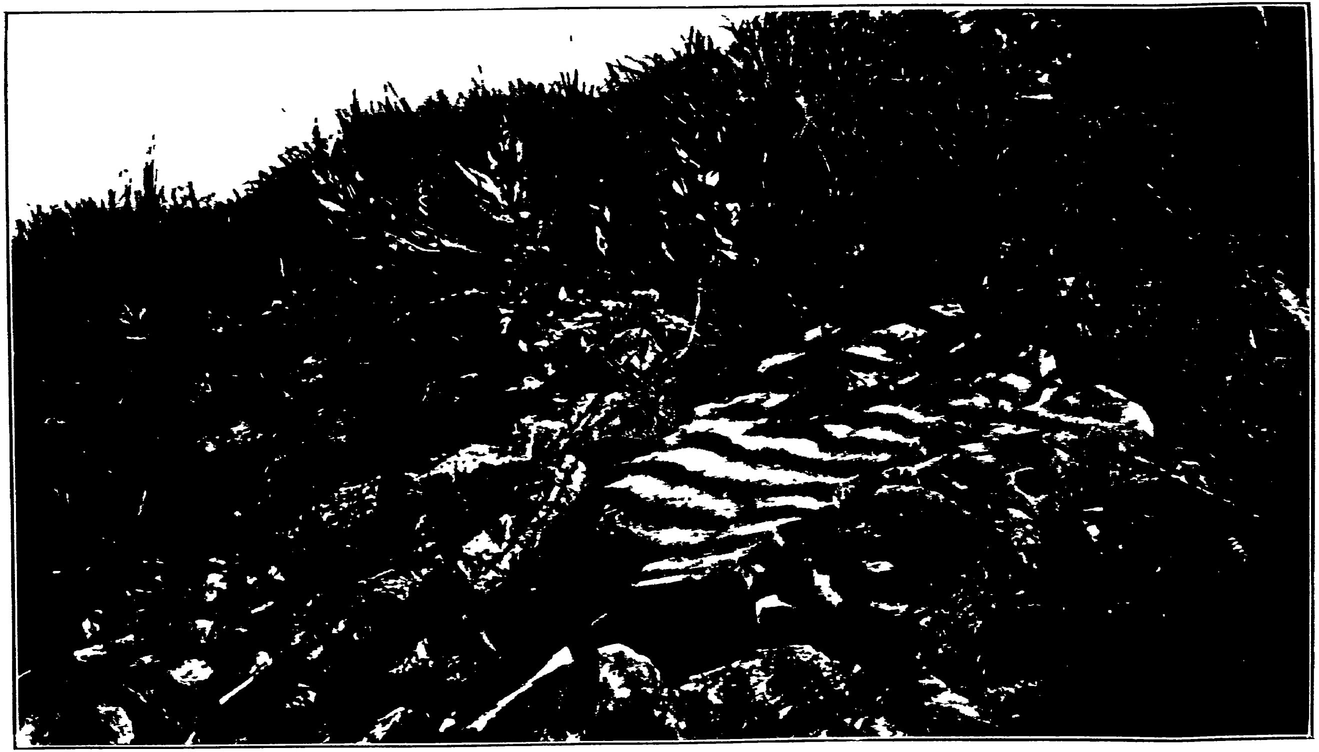
Ripple-Marks.—These may be frequently seen in the sands laid down on the sandy shore of a lake or sea, or on the floor of a shallow lake or estuary. The latter are produced by the pulsations of a slowly retreating tide. They are also formed by the wind bearing on the surface of shallow, slowly-ebbing, tidal waters. The ripple-marks produced by one ebbing tide will be obliterated by the next flowing tide, which, on retreating, will form a new series of ripples.

In certain situations the surface of sand dunes is frequently covered with parallel ripple-marks formed by oscillations in the force of the wind.

Where the ripple-marks are formed under water that is always receiving fresh accessions of sand, a ripple-marked surface may be gently overspread with a layer of sand and be thus preserved (Plate XII.). Ripple-marked sandstones are found among the geological formations of all ages.

Sun-Cracks.—In many shallow tidal harbours, estuaries, and deltas, a marginal strip of silt or mud is daily left high and dry between the high-water and low-water lines. At the upper limits of the tide the sediments may be exposed to the drying influence of the sun's rays for many hours at a time; and when this happens the muds shrink, and in doing so become seamed with a network of cracks that produce polygonal cakes somewhat resembling the pattern of an ancient Roman pavement (fig. 59).

Sun-cracked muds are a striking feature in many mangrove-covered tidal harbours in north New Zealand, Australia, East Indies, and other tropical and semi-tropical lands where the blazing heat of the summer sun at certain phases of the tide dries up the marginal layers of mud with great rapidity. The same



RIPPLE-MARKS IN BURKE FORMATION ON TIGER PEAK. (U.S. Geol. Survey.)

phenomenon on a miniature scale may be witnessed in almost all temperate lands in dried-up mud-puddles and pools on the roadside, and in cultivated fields after heavy rain followed by sunshine or a drying wind.

Estuarine and tidal sun-cracks are usually obliterated by the next tide, but in some cases they are gently filled with fine sediment and thereby preserved.

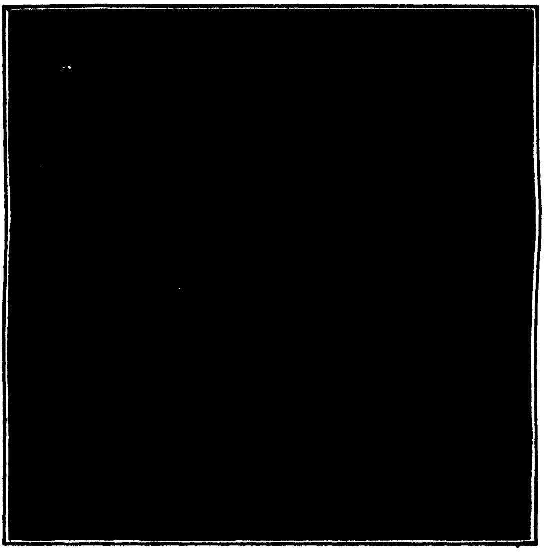


Fig. 59.—Showing sun-cracks in harbour mud.

Fossil sun-cracks are eloquent witnesses of tidal muds and a blazing sun in past geological ages.

Rain- and Hail-Prints.—Estuarine muds are sometimes pitted with the heavy drops of a passing shower of hail or rain, and when these prints are gently covered with mud by a slowly rising tide they are permanently preserved, thus forming valuable meteorological records.

Where the mud is very soft, the rain only makes indistinct splashes, and where it is too hard, it fails to make any impression. But in tropical and semi-tropical lands, hail frequently falls as large as hazel-nuts. In a few minutes it litters the ground with leaves stripped from the fringing mangrove trees, and in the open estuary descends with such force that much of it is half-buried in the partially dried mud. When the half-buried hail melts, it leaves perfect dimples or prints scattered irregularly over the surface of the mud. Many, if not the majority, of the supposed fossil rain-prints are probably hail-prints.

Fossil-prints have been found in many geological formations, and their values lie in the proofs they afford that the meteorological conditions of to-day are but a continuance of those that existed in far-off geological times.

Animal Trails.—Crabs, lobsters, shellfish, and worms as they move over the surface of the partially dried silts and muds exposed between tide-marks, leave their trails and burrows, which, under favourable circumstances, may be preserved by a fresh layer of sediment. Marks such as these have been found in rocks composed of fine sand and mud; and are regarded with much interest

by geologists as they afford conclusive proof of the physical conditions under which the sediments were laid down.

Besides these, there have also been preserved in slabs of stone the tracks of reptiles, birds, and mammals that in past ages roamed about the margins of the sun-dried estuaries and deltas in search of food. In the Newark system of the Connecticut Valley they are the record of a rich organic life.

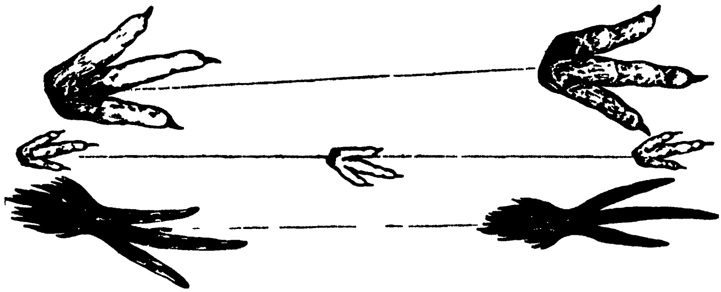


FIG. 60.—Showing animal tracks.

SUMMARY.

The rock-structures that have been considered in this chapter are (1) *Stratification*, (2) *Lamination*, and (3) *False-bedding*.

(1) *Stratification* refers to the arrangement of detrital material in parallel layers or beds commonly termed *strata*; a word derived from the Latin *stratum*=a layer or bed. When the different beds (exposed, for example, in a sea-cliff) are distinctly marked, the rocks are said to be *well-stratified*. But if, on the other hand, the bedding is indistinct and difficult to determine, the rock is said to be *indistinctly stratified*. Thin bands of any material occurring at intervals in a formation that possesses no bedding planes, always impart a stratified appearance to the rock. A line of detached nodules or pebbles will also indicate the original deposition plane in a rock that otherwise shows no evidence of bedding.

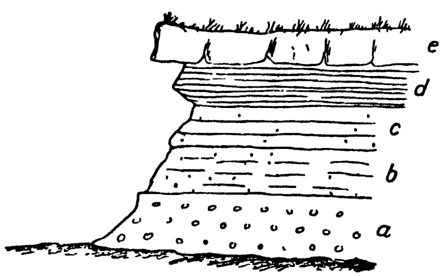
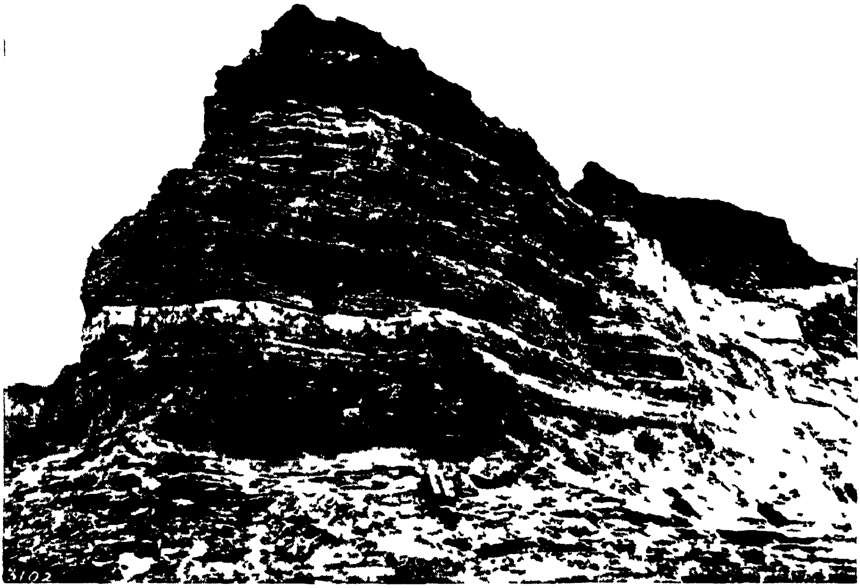


FIG. 61.—Showing section of stratified rocks.

(*a*) Conglomerate. (*c*) Thin-bedded sandstone.
(*b*) Thick-bedded sandstone. (*d*) Marly clays.
(*e*) Marine limestone.

The appearance of well-stratified rocks in many sea-cliffs is shown in fig. 61, and in Plate XIII. (A).



A. Horizontal Pliocene Strata, New Zealand

B. Inclined Strata

(2) *Lamination* refers to the aqueous deposition of silt and mud in very thin layers or *laminæ*. Lamination is merely a minute form of stratification, and is a structure found only in fine sediments deposited in still or slowly moving waters in accordance with the principle of equal-falling particles.

(3) When the planes of stratification in some particular bed run at some other angle than the general plane of the beds above and below, the structure is termed *false-bedding* or *current-bedding*.

The appearance of false-bedding in consolidated or partially consolidated rocks is shown in fig. 62.

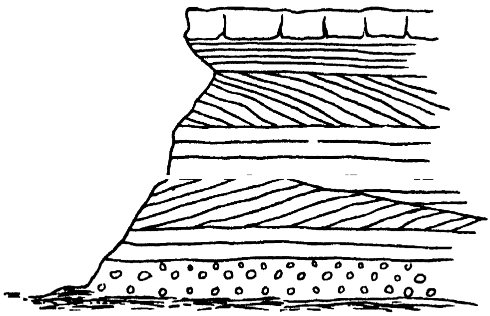


Fig. 62.—Showing false-bedding structure.

False-bedding is found in fluviatile, lacustrine, and marine deposits, as well as in wind-borne sands. It is frequently a local phenomenon due to the action of eddies, back-water currents, and the tipping of sediments into comparatively still deep water. It should, however, be noted that false-bedding is not necessarily limited to local occurrences. False-bedding can sometimes be traced in a particular stratum for miles. For example, the famous *Desert Sandstone* of Northern Australia exhibits this peculiar structure extending over hundreds of square miles.

(4) Ripple-marks, sun-cracks, rain-prints, and animal tracks are found preserved in rocks. They are an evidence of the prevalence of shore-line conditions at the place where the sediments were laid down. They also afford valuable evidence as to the meteorological conditions of far-away geological ages.

(5) It is a geological axiom that all the mechanically formed sediments laid down on the floor of the sea were formed of the waste of pre-existing land.

(6) Another axiom of extraordinary value in solving problems relating to the distribution of land and sea in past geological ages is that all marine detrital sediments were laid down on the sea-floor marginal to land areas existing at the time. The only notable exception to this generalisation are the accumulations of ash and lava piled up on the sea-floor by submarine volcanic eruptions.

CHAPTER IX.

ROCK STRUCTURES.

The Consolidation of Sediments.

In the last chapter we were principally concerned with the manner in which the products of denudation in the form of coarse and fine sediments were spread out in parallel layers and piled up on the sea-floor and in lake-basins. These sediments are the materials of which stratified rocks are formed.

When we speak of a rock we at once form a mental picture of something hard and compact. As a matter of fact, some rocks are soft and others very hard. A marl or clay, for example, is very soft and friable; while a sandstone may be intensely hard.

Sedimentary rocks, as usually defined, are composed of sediments that are more or less *hardened* or *consolidated*; and although originally laid down in a horizontal or approximately horizontal position, they may be now found *tilted* or *inclined* at various angles, and thrown into *folds* that may be gentle *undulations* or minute *corrugations*.

Moreover, closer examination soon discloses the fact that the rocks have not only been pushed into folds and corrugations, but also *fissured* with many small *cracks* or *joints*, and occasionally traversed by great *dislocations* or *fractures* termed *faults*.

Everywhere there is evidence that the rocks have been at one time or another subjected to enormous *stress* or *pressure* whereby they have been folded, crumpled, tilted, fissured, or fractured as mentioned above.

Our aim in this chapter will be to consider the various processes by which soft and incoherent sediments may be consolidated or hardened into what is called rock or stone.

Hardening of Sediments.

The hardening of sediments may be effected (*a*) by *pressure* or (*b*) by a *cementing medium*.

Hardening by Pressure.—This is the simplest and most obvious means of consolidation, and whether the pressure is effected by natural or artificial agency, the results are always the same. Thus, when clay is placed in a mould and subjected to great pressure, it is converted into a brick or tile as compact as an ordinary shale.

The same thing takes place in Nature. When clay, mud, or fine silt is subjected to the pressure of hundreds of feet of overlying sediment, it is converted into a shale or claystone.

In its plastic condition, clay exists in the colloidal state, and like all colloids, when mixed with water, it forms a paste. In a shale or slate the clay is no longer a colloid.

Coarse sediments are not easily consolidated by mere pressure alone; but if they consist of particles of various sizes that will fill up the interstices between the larger grains or pebbles, or if they contain an admixture of muddy paste, they may be consolidated into a fairly hard rock by pressure alone.

When sediments are deposited in water they are loose and incoherent, this condition being mainly due to the interstitial water which tends to keep the constituent particles apart. By the action of pressure much of the interstitial water is expelled, and a closer contact is thereby established between the particles.

The principle underlying consolidation by pressure is that fine sediments afford a larger adhesive surface relatively to the size of the constituent particles than coarse sediments.

Hardening by a Cementing Medium.—The process of hardening by a cementing medium may be easily illustrated by a simple experiment. Take *four* ounces of Portland cement, *six* ounces of clean sand, and *six* ounces of pebbles of the size of peas.

Place these constituents on a flat plate or board and mix thoroughly in a dry state.

Pile the mixture into the form of a flat truncated cone. Make a hole in the middle of the cone and into it pour *two* ounces of clean water.

With two spatulas, one in each hand, work the mixture and water into a thick paste, adding a *little* more water if required. Turn the paste over for several minutes until the water is thoroughly incorporated, and then press it firmly into a mould of any shape. A small cigar-box will do very well. After two or three hours remove the hardened mass from the box and you will have a slab of rock artificially formed.

This experiment is not intended to illustrate the chemical process of setting so much as the part played by the cement in binding the sand and grit into a hard aggregate. The cement is merely an artificial *matrix* in which the sand and grit are embedded. If moistened with water and placed in the mould, it would form a slab of fine-grained artificial stone much stronger than that obtained in our experiment.

In the making of concrete, which is merely an artificial stone, it is found that the greater the proportion of constituent aggregates, such as sand, gravel, or broken rock, to the cement or matrix, the weaker is the resulting concrete; and such also is found to be the case in Nature. It has been proved experimentally that of all rocks slate possesses by far the greatest tensile and shearing strength.

Take again the case of the frozen gold-bearing gravels in Siberia and Alaska. The contained water freezes for a depth of a few inches or many feet, according to the length and severity of the winter frosts, and hardens the whole mass into a rock-like mass resembling a conglomerate. Here the frozen water is the cementing medium or *matrix*, and although the hardening is only *temporary* it very well illustrates the formation of conglomerates.

The permanent hardening of sediments by a cementing medium is effected in Nature by the deposition of mineral matter between the constituent particles from waters slowly circulating through the mass.

The commonest natural cementing media are *carbonate of lime, oxide of iron,* and *silica.*

Carbonate of lime and some *iron compounds* are soluble in water charged with carbonic acid gas, and may be deposited as carbonates if the water evaporates or becomes saturated, or if the carbonic acid becomes disengaged as it does quite readily by agitation or decrease of pressure, being what is known

as a weak acid—that is, an acid which possesses but a feeble hold of the substances with which it combines.

The deposit or precipitate of carbonate of lime or iron acts as a cementing medium and binds the surrounding particles into a coherent mass. In this way sands are converted into sandstones, and gravels into conglomerates.

When the carbonate of iron is deposited among porous sands or gravels, it becomes in the presence of water converted into the rusty brown hydrous oxide called *limonite*. Hence we find that the cementing medium of ferruginous sandstones, gritstones, and conglomerates is in almost all cases the hydrous oxide of iron.

On the other hand, when carbonate of iron is precipitated in a fine impervious sediment, it remains as the carbonate, forming the well-known clay-band ironstone—a valuable ore of iron that occurs in formations of all geological ages.

Silica is perhaps more abundant as a cementing matrix than carbonate of lime, particularly among the older rocks. It is soluble in waters containing potash or soda, especially at high temperatures. Deep-seated waters are usually *alkaline* from the presence of dissolved salts of potash or soda. These waters in their passage through the rocks dissolve silica, and when they rise to a cooler stratum, the silica is deposited around and between the particles, which are thereby cemented into a compact rock.

Siliceous waters are frequently abundant in regions of waning volcanic activity, where they appear in the form of hot springs and geysers. The potash or soda has a greater liking or affinity for the carbonic acid of the atmosphere than for the silica. It consequently forms a new partnership, thereby liberating the silica which is deposited as an incrustation of sinter around the outlet of the spring or geyser from which the waters issue. Moreover, sands and gravels that happen to lie near are cemented into hard rock.

These siliceous waters also possess a petrifying power, such organic substances as leaves, twigs, and even animal remains being replaced by silica, the replacement taking place so slowly as frequently to reproduce in stone the exact form and structure of the original organism.

From the foregoing we find that a stratum of sand may be cemented with carbonate of lime, oxide of iron, or silica.

The carbonate of lime forms a *calcareous sandstone*; the oxide of iron, a *ferruginous* or *limonitic sandstone*; and silica, a *siliceous sandstone*. That is, the nature of the sandstone and of the qualifying adjective depends on the character of the cementing matrix. Similarly, we may have a *calcareous conglomerate*, a *limonitic conglomerate*, or a *siliceous conglomerate*. If the conglomerate is mainly composed of quartz or quartzite pebbles set in a siliceous matrix, like the famous banket reefs of the Witswatersrand, it could be very well described as a siliceous quartzose conglomerate.

When a pile of sediments consists of alternating layers of mud and sands, the sandy beds are in many cases found to be cemented into a hard resistant rock, while the layers of mud or clay remain relatively soft. Such hard bands may be seen standing out as projecting ledges in many sea-cliffs and escarpments.

The hardening of the sandy beds is in most cases due to the deposition in them of a cementing medium. The clayey beds being impervious to water only attain the moderate degree of hardness that can be imparted by pressure and dehydration; whereas the sandy beds being porous offer a free passage for the flow of mineral-laden waters which leave behind them a deposit of cementing material.

The coral reefs and coralline beach-sands of the tropics, as well as the shelly

sands and shell-banks found on the strands of nearly all lands, have been in many places converted into compact limestones by the partial or complete dissolution and replacement of the corals and shells by carbonate of lime in a semi-crystalline or crystalline form in which there is usually no trace of the original organisms.

Other Cementing Media.—Among other, but less common, cementing materials deposited among sediments by mineralised waters are *carbonate of magnesia*, *sulphate of lime*, *sulphate of barium*, and *oxides of manganese.*

Carbonate of lime is a comparatively soft substance; consequently the rocks in which it is the cementing medium are seldom capable of withstanding much wear and tear. Besides this, a calcium carbonate matrix is readily dissolved by rain water. For this cause alone the disintegration of calcareous rocks is relatively rapid.

On the other hand, silica is an exceeding hard substance and practically insoluble in atmospheric gases. Hence siliceous sandstones and conglomerates are always hard rocks capable of withstanding a great amount of mechanical or chemical erosion.

Limonitic sandstones are frequently soft and friable, but many limonitic quartzose conglomerates and grits possess great resisting power.

Concretions.—It frequently happens that only isolated portions of a bed or stratum are hardened by the cementing medium. These hardened portions

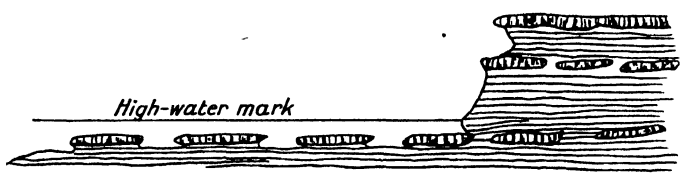


FIG. 63.—Showing tabular concretions.

or *concretions* have been formed by the operation of a well-known physio-chemical law in accordance with which salts in solution are attracted to the points of greatest concentration. They may occur close together or widely scattered.

Concretions[1] are usually spheroidal in form, and for that reason are sometimes mistaken for pebbles or water-worn boulders. They may range in size from a few inches up to ten feet or more in diameter. They are frequently composed of concentric layers that peel off in concentric layers till a solid spheroidal core is reached. This spheroid on close examination is frequently found to have formed round some organic body, such as a shell or saurian bone, as a nucleus.

In many cases the internal portion of the concretion has contracted more than the external, thereby giving rise to numerous radiating cracks that have subsequently become filled with calcite. Concretions possessing this structure are sometimes called *septarian boulders*, or simply *septaria*, this name arising from the many-sided segments into which they are divided by the calcite-filled cracks.

Concretions are commonly found in shales and clays. They are often covered with an outer layer of argillaceous limestone that possesses the peculiar *cone-in-cone* structure.

[1] From the Latin *con*=together, and *cretus*=grown.

Concretions in which carbonate of iron is the cementing medium are sometimes quite common in clays and shales, but they seldom attain the dimensions of septaria.

Clays sometimes contain nodular-shaped concretions composed of limestone, oxide of iron, or iron pyrites. These concretions frequently assume grotesque forms that sometimes bear a quaint resemblance to organic bodies or to objects fashioned by the hand of primitive man. Many of these nodules are hollow, the cavity being lined with crystals.

The hardened portions of a stratum are frequently lenticular or tabular in form, and lie so close together as almost to form a continuous band of hard rock, as shown in fig. 63. This structure is due to the separation of the carbonate of lime from the remainder of the rock, and its concentration in certain layers or tabular masses.

Some concretions were probably formed during the accumulation of the sediments in which they lie, but the majority have arisen from a rearrangement and concentration of like kinds of mineral matter.

Flints.—These occur as grey, red, brown, or black nodules dispersed in limestones, chalk, etc. They are well known in certain layers of the Upper Chalk of England. They frequently enclose some organism, such as a sponge, echinoderm, or shell, the organism being the nucleus round which the siliceous concentration took place.

In some places, as in Marlborough and Kaipara in New Zealand, the flint forms distinct beds many feet thick in the Middle Cretaceous.

Flint possesses a perfect conchoidal fracture. The dark colour of the black variety arises from the presence of carbonaceous matter, which can be dispelled by heat.

Flint nodules are formed by the interchange of carbonate of lime and silica. Many marine plants and animals secrete silica from sea-water for the building up of their organisms. The water present in the chalk dissolves these organisms, and as it does so, replaces them with carbonate of lime. The water now charged with silica deposits the silica elsewhere, preferably where some of it already exists, as, for example, on sponge-skeletons, which consist of siliceous spicules.

In cases where the calcareous shell of an echinoderm or a coral has been replaced by silica, it would seem that the dissolution of the carbonate of lime was accompanied by direct replacement with silica, molecule by molecule, the process being similar to the replacement of shells by iron pyrites, which has so frequently taken place in clays and shales.

Such replacement of one mineral by another is called *pseudomorphism*.[1]

Fulgurites.—As a geological agent lightning is not of much importance. It is reputed to be capable of shattering solid rocks, but its usual effect is to perforate their surface with small holes lined with a glassy enamel. When the electric spark is discharged into sand or loose soil, it may form short, tapering, fragile tubes of partially fused sand-grains called *fulgurites*.

The Tectites.

The *tectites* are mineral bodies of doubtful origin. They consist of a yellowish, brown, black, or green glass and are of various shapes: balls, triaxial ellipsoids, tears, pears, dumb-bells. The surface shows navels, grafters, striæ, and grooves. The single occurrences of these tectites have been called

[1] From the Gr. *pseÿdos*=false, and *morphe*=form.

with different names: *Moldavites*, which occur in Bohemia and Moravia; *Billitonites* in the southern half of Billiton (Malay Archipelago); *Australites*, scattered over a large area in southern Australia and a portion of Tasmania, and others. The tectites show a similarity to obsidians, but their chemical constitution differs from that of any terrestrial igneous rock. The Moldavites, Billitonites, and Australites occur in loose, sandy sediments and gravels of late Tertiary or old Pleistocene age, and are found, *e.g.* in Billiton, always immediately upon the bed-rock. Doubtless all tectites belong to the same family and are of the same origin. Concerning the latter different hypothesis have been pronounced. Some investigators urged a terrestrial origin and a volcanic nature, regarding the tectites as acid ejectamenta. Others believed them to be artificial products. Verbeek assumed that they had fallen from the moon, being volcanic bombs of the moon volcanoes. Krause and F. E. Suess propagated the cosmic origin of the tectites. This idea is generally accepted. One supposes that the tectites are parts of the outer shell of meteoric bodies, from which the meteorites originate. Wing Easton suggests that the tectites are originally a colloidal mass, out of which the moisture escaped by diffusion and evaporated at the surface. The mass gradually dried up and ultimately vitrified. An important rôle in this process is attributed to the action of humic acid.

CHAPTER X.

DEFORMING OR DIASTROPHIC EARTH-MOVEMENTS AND EARTHQUAKES.

Earth-movement may take the form of uplift or subsidence, rock-folding or faulting, shearing or horizontal displacement. Moreover, it may be *local* or *continental*, *slow* or *rapid*.

Local movements are usually due to volcanic agency, earthquakes, or faulting. They are relatively rapid, and may cause sharp folding and displacement of strata in the neighbourhood of the disturbance.

The movement which affects continents or large areas is usually slow, and may not amount to more than a few inches in a century. Such slow regional movement is called *secular movement*, as it is more or less continuous over a number of years.

An upward crustal movement, which eventually results in the formation or building up of a land-surface of continental dimensions, is called *epeirogenic*;[1] while an upward linear folding of the strata, which eventually uplifts mountain-chains, is called *orogenic*.[2]

SLOW ELEVATION AND SUBSIDENCE OF THE LAND.

Elevation.

When we find strata containing marine shells forming masses of dry land, hundreds or may be thousands of feet above the sea-level datum, we are compelled to conclude that the land has emerged from the sea. These shelly beds represent the uplifted sea-floor of some past geological age.

Among the best evidences of recent uplift are what are called *raised beaches*, which is only another name for uplifted sea-strands. These occur on the shores of many lands in both hemispheres, being strikingly conspicuous on the coasts of Scotland, England, Norway, Sweden, Spain, South Italy, Sicily, Morocco, Algeria, Egypt, Pacific side of North and South America, India, Australia, and New Zealand. They form benches or terraces that in some cases can be traced along the coast-line for scores and even hundreds of miles, curving round headlands and following the various indentations of deep bays and long fiords (Pl. XIV.).

Raised beaches consist of shingle and sand mixed with sea-shells, the majority of which belong to species still living in the adjacent seas. They are usually backed by cliffs that are frequently wave-worn and undercut or hollowed into caves. In some cases the rocks are covered with barnacles or perforated with holes bored by marine shells.

In the fiords of Norway[3] raised beaches occur at heights varying from 50 to 600 feet above the sea, and singularly enough they are not horizontal but

[1] Gr. *epeiros*=a continent, and *genesis*=production.

[2] Gr. *oros*=a mountain, and *genesis*=production.

[3] Professor E. Hull, "The Physical History of the Norwegian Fiords," *Geol. Mag.*, Jan. 1913, pp. 9–14.

RAISED WAVE-CUT MARINE TERRACE, NORTH OF PORT HARFORD, CALIFORNIA.

slope gently towards the sea, which is an evidence that the rate of uplift has been more rapid on the landward than seaward side. This unequal rate is what is termed *differential uplift*.

In Scotland raised beaches can be traced at 25, 40, 50, 60, 75, and 100 feet above the present sea-level.

The occurrence of marine shells in rocks involved in the great earth-folds which comprise the Alps, Himalayas, and other mountain-chains, affords incontestable proof of uplift in bygone geological times. Raised beaches are records of comparatively recent elevation; and we have abundant evidence that elevation is still in progress in some parts of the globe. It is doubtful if the land is ever in a state of complete rest for any considerable time. If it is not rising, it is probably sinking; and it frequently happens that uplift on one side of a continent is compensated by subsidence on the other. Marks placed on the coast of Sweden in 1820 have shown that the land is still rising at the rate of 2 or 3 feet in a century.

Subsidence.

The evidences of subsidence are not always so obvious as those of uplift, as they are mostly to be found submerged in the sea. Among the most conclusive proofs are submerged coal-seams, submerged forests, and buildings. To these might be added fiords and drowned valleys.

Submerged Coal.—At the present time seams of coal are being worked many hundred feet below sea-level in Scotland, England, Belgium, United States, and New South Wales. Now coal, as we know, consists of the remains of vegetation that required sunshine and air for its growth. It was formed on the dry land, and is what is called a *terrestrial deposit*. When, therefore, we find it hundreds and in some cases thousands of feet below the present level of the sea, we are safe in concluding that a subsidence of the old land-surface, on which the coal vegetation grew, has taken place at some remote period.

Submerged Forests.—The erect stumps of forest trees, frequently associated with peaty matter containing twigs, leaves, and fruits, are found below sea-level in many lands. Good examples are seen at Formby Point on the coast of Lancashire; at Leasowe, in Cheshire; and at Freshwater West, in Pembrokeshire. Such submerged forests are an evidence of subsidence in quite late geological times or of coastal sag.

Drowned Valleys.—The celebrated fiords of Norway and New Zealand, that stretch far back among the neighbouring mountain-chains, are merely deep mountain glens that have been invaded by the sea. In California and other lands the soundings show that some of the existing valleys can still be traced far seaward. That is, river-valleys are found to be continuous with valleys in the sea-floor. This is rightly held to be proof of comparatively recent subsidence of the coast-line.

The broken, deeply indented, and ragged coasts of British Columbia, Alaska, North-East Canada, and Greenland have originated from a general subsidence of the previously deeply dissected maritime lands in these regions, or, eventually, by a rise of the sea.

Barrier Reefs and Atolls.—According to Darwin's view, these are coral reefs that have grown upward on a sinking sea-floor. The borings conducted at the island of Funafuti proved the existence of coral reefs and coral limestone down to a depth of 1114·5 feet below sea-level; and since the coral polyp can only live in comparatively shallow water, extensive subsidence, probably amounting

to 800 feet, must have taken place since the foundations of the existing coral reefs were formed by the coral-builders.

EARTHQUAKES.

Classification of Earthquakes.—In a general way earthquakes, according to their origin, may be divided into—

(1) Volcanic type. (2) Geotectonic type.

Volcanic Earthquakes.—Earthquakes of this type are directly or indirectly associated with volcanic activity. They are common in connection with eruptions of the explosive type, and may often precede the actual eruption. Premonitory rumblings and earth tremors frequently continue for many hours, or even days, before the actual outburst takes place. Earthquakes of volcanic origin are often of great intensity and destructiveness, but as a rule they originate near the surface and hence are limited to a narrow radius around the centre of activity.

Geotectonic Earthquakes.—These are connected with mountain-building, and are the result of the crustal movements that originate intense folding and fracturing of rock-masses. As we should expect, earthquakes of this type are common in regions that have undergone relatively rapid uplift or subsidence. They often occur in mountain regions where denudation, by shifting the superincumbent load, permits deeply buried folds, existing in a state of stress, to find relief by fresh adjustments. The adjustments usually take place along old lines of fracture, though they may develop new fractures. It has long been suspected that many earthquakes were originated by fault-slipping. So far back as 1855, Osmond Fisher attributed the Visp earthquake of that year to the growth of a fault.

Crustal adjustment is accomplished by sudden jolts that propagate waves of elastic compression within the crust. It is the emergence of an earth-wave at the surface that causes the actual tremor or quake.

Milne compares the progress of an earth-wave to the concentric rings formed in water when a stone is thrown into it; but the two waves are not of the same kind. A water-wave is propagated by gravity, while an earth-wave may be compared to the vibrations generated when a weight suspended by a string is struck from below, the vibrations travelling upward. In the case of a rock-block that receives a blow or impulse from below, the vibrations travel upward and radiate outward concentrically.

The place at which the original impulse or motion originates is called the **origin, centrum,** or **focus**; and the shortest line by which the earth-wave reaches the surface is called the **seismic vertical.** The point of emergence over the centrum is called the **epicentrum.** The distance through which any vibrating particle of the Earth's crust moves to and fro under the impulse of an earth-wave is called the **range** of the vibration; and half the range, or the distance the particle moves from its mean position, is called the **amplitude.**

The impulse is also directed laterally in lines of concentric rings that also reach the surface and are called **coseismic rings.** The further the wave travels from the centrum the more obliquely will it strike the surface. If the disturbance arises along a fissure, the coseismic rings when plotted assume, more or less, the form of ellipses.

Many methods have been suggested for the determination of the depth of the original impulse, but none gives trustworthy results. Of the two methods most favoured that of Milne is based on the assumption that the relative depths

of earthquake *foci* may be inferred from the intensity of the respective shocks compared with the extent of the area affected. It is believed that if the shocks are slight at the epicentrum, but affect a wide area, the seat of disturbance is likely to be at a greater depth than in the case of an earthquake of like intensity felt over a smaller area. Mallet's method is based on what is called the **angle of emergence.** The cracks produced in buildings are assumed to be perpendicular to the plane of emergence. If a sufficient number of observations can be taken, the angles of emergence are calculated in relation to their convergence in depth, and the point of convergence gives the depth of the initial impulse. The results obtained by these methods are often discordant and hence unsatisfactory. At one time Milne thought that earthquakes originated at from 20 to 30 miles depth, but recent observations tend to show that the maximum rarely exceeds ten miles, and that most originate within five miles.

It has been proved experimentally that the elasticity of solid rocks is greater than that of unconsolidated sands and gravels. Therefore the retardation of an earth-wave is greatest in the incoherent material and least in the solid. Hence houses built on alluvial plains as a rule suffer more damage from earthquakes than those built on solid rock. Faults, cracks, and zones of shattered rock, that lie athwart the path of the wave, also modify the velocity and destructiveness of earthquakes. And in this we find an explanation of the variable destructiveness of earthquakes. A violent earthquake may destroy some parts of a city, while other parts escape with little or no damage. But the subject is complex, and the phenomena of the simplest earthquake may present many problems some of which are not easy to solve. And the problems are still further complicated when impulses start simultaneously from two or more foci, as may happen when settlement takes place along a fault fracture.

The simple or normal earthquake has a single focus, and the vibrations begin in slight tremors that reach a maximum of amplitude and thereafter gradually decline. Normal earthquakes are supposed by some seismologists to be associated with displacement along the plane of strike-faults. Twin and compound earthquakes, though less frequent, are often intense. They are believed to be associated with settlement along the plane of dip-faults, but the exceptions are so numerous that generalisations based on this assumption must be regarded with caution.

Distribution of Earthquakes.—On account of the unequal and ever-changing stresses that are developed on steep continental slopes by earth-creep, acting under the influence of gravity and the unloading due to denudation, earthquakes are specially frequent along the borders of the great continents. But more earthquakes originate in the floor of the ocean than on land. Submarine earthquakes propagate sea-waves, sometimes called tidal or seismic waves, that are often of great height, and specially destructive over low-lying coastal lands. As a rule, before the final onrush, the sea recedes rapidly from the shore, and then gathering itself into a tremendous wave rushes on the land with irresistible force. Seismic waves as high as 80 feet have been recorded. The seismic wave that accompanied the earthquake, which devastated the coast of Chile, on 10th November 1922, is reported to have exceeded a height of 80 feet.

Certain belts of the Earth's surface are specially liable to earthquakes. One great belt encircles the globe, following the main mountain-chains in the Northern Hemisphere. This broad belt passes from north-west Africa and Southern Europe to Asia Minor, Persia, India, China, Japan, whence it crosses the Pacific then traverses California, Central America, and the West Indies, then crosses the Atlantic by way of the Azores and Teneriffe. From the great east and west belt prolongations go north and south, following the course of

the great meridional chains, such as the Andes and Rocky Mountains, the Malay Peninsula, and New Zealand. It has been observed that earthquakes are most frequent where there is the greatest contrasts in surface configuration. Montessus de Ballore agreed with Milne in the following conclusions relating to the geographical distribution of earthquakes :—

1. That in a group of adjacent seismic regions, the most unstable are those that present the greatest difference of topographic relief.
2. That unstable regions are associated with great lines of elevation. Thus the Mediterranean Alps-Caucasus-Himalaya circle receives 53·54 per cent. of the shocks ; and the circum-Pacific, forming the Andes-Japan-Malay circle, 41·05 per cent. of the shocks.
3. That rapidly deepening littorals, especially if they border important mountain ranges, are unstable ; while gently sloping littorals are stable, especially in the case of flat coasts.

It should be noted that these generalisations refer only to *seismic regions*, and not to seismic centres individually.

Japanese Earthquake (1923).—On the 1st September Tokio, Yokohama, and scores of villages were laid in ruins in the short space of thirty seconds by the most destructive earthquake in the history of mankind. Fire rapidly swept over the shattered cities causing an appalling loss ot life and property. On the 12th September the official compilation of the casualties estimated the killed, wounded, and missing at 1,356,000. The range of the disaster extended from Osaka northward 300 miles. The main centre of disturbance was near the celebrated Mount Fugi. Hakone, a famous mountain resort, was almost obliterated, with great loss of life. The Japanese are facing this almost overwhelming catastrophe with a courage and devotion that has enlisted for them the sympathy of all nations.

Geological Effects of Earthquakes.

The most important effects of earthquakes are seen in the permanent changes in the level of the land which they cause. Changes of level of this kind have been recorded in Chile, India, Japan, and New Zealand. At the same time it is well to accept the reported evidences of uplift with caution. Most of the reported cases of uplift have been in connection with coastal areas inundated by the sea-waves that accompany great earthquakes. The sea-wave by its tremendous momentum picks up and carries shoreward a vast quantity of beach-sand and shells. At the limits where its progress is checked, it deposits its load in the form of a storm-beach or shelf that contours around the shore. The *pseudo-beach* thus formed may easily give an appearance of uplift that is quite erroneous.

The great earthquake that took place in the Cook Strait area, Wellington (N.Z.), in 1855 is reported to have permanently raised a tract of land, 4600 square miles in extent, to a maximum height of 9 feet. At the same time a fissure opened at the surface along the foot of the Rimutaka Range, forming a gaping chasm from 2 to 9 feet wide, and traceable for a distance of 90 miles along the western border of the Wairarapa Plain—that is, along the east side of the range. W. T. L. Travers (1868) stated that the sea-wave accompanying this earthquake was over 30 feet in height, and this estimate was confirmed by the Hon. Walter Mantell and Hon. R. Pharazyn, both of whom remembered the occurrence.[1]

In the early seventies a raised beach composed of sand and broken shells contoured around Lambton Quay, the Basin Reserve, and Oriental Bay, Wellington, at a height of about 9 feet above high-water mark. It was described to the writer (1874) as an effect of the earth-

[1] *Trans. N.Z. Inst.*, vol. i., 1868, p. 47.

quake of 1855. The evidence as to actual uplift of the land around Port Nicholson by the earthquake of 1855 is not satisfactory, being mainly based on the occurrence of this raised beach, which may after all have been formed by the impetuous inrush of the sea-waves, as described by Travers.

After the submarine earthquakes in July 1890, the electric cables between Australia and the outer world were broken. Off the coast of Java the repairing vessel found large portions of the sea-floor, that previously were nearly level, sunken in a peculiar manner. A great submarine depression had been formed, bordered by steep cliffs. The inner area consisted of a mass of fractured rocks, that had sunken from 1500 to 4800 feet below their former level. It was this sudden collapse of a portion of the sea-floor that had severed the submarine cables.[1]

The theory of the propagation of shocks was formulated by mathematicians, and it became possible to predict from the nature of the records at one station, the position of disturbances at the other end of the world. Seismographs have confirmed the inferences derived from the local study of earthquake effects. It is now known that earthquakes are secondary, not primary events. It is the deep-seated cause of the local shaking that sends the earth-waves through the world. Dr. R. D. Oldham has given the name "bathyseism" to the deep-seated disturbance, the focus of which might be placed as deep as one-tenth of the earth's diameter from the surface.

Shocks of great intensity may crack and overthrow buildings, fracture rocks, fissure the ground, propagate earth-waves and tidal waves. On steep slopes rocks may become detached, or even land-slips may be started.

Earthquakes that originate at fault-planes may throw down forests, shatter rocks, and cause other destruction for hundreds of miles along the line of fracture or dislocation. Shocks resulting from volcanic explosions are frequently sharp and destructive, but the effects are local and confined to the volcanic zone, which may be bounded by fault-planes.

The standing pillars of the Temple of Jupiter Serapis in the Bay of Baiae, a few miles north of Naples, are an example of the extreme steadiness of the subsidence and elevation that may take place even in a volcanic region where the movement is relatively rapid.

The ruins stand within a stone's-throw of the water's edge, and on all sides are extinct craters. Less than a mile to the north-east lies the well-known crater of Solfatara, still in the expiring stages of volcanic activity; and about two miles to the north-west is the symmetrical cone of Monte Nuovo.

Three standing marble pillars rise from a level pavement. About 10½ feet from the base the columns are pitted with holes made by boring molluscs. The length of column pitted in this way is a little over 8 feet. Near the top of the perforated portion there is a slight annular indentation, in all probability the work of marine erosion, which would indicate that the land remained stationary at that point for some time.

The presence of the borings proves that the pillars must have been submerged in sea-water for some considerable time and afterwards elevated to their present level. The original height of the temple above sea-level is not known. The level of the platform is still a little below high-water mark, and a second platform exists 5 feet below the first, indicating that an earlier subsidence had rendered it necessary to construct a new floor at a higher level. Therefore, within historic times, we have proof of an up-and-down vertical movement amounting to 45 feet, on the assumption that the original lower floor was only 2 feet above high-water mark when first constructed.

Raised shelly strands and other evidences of recent elevation may be seen all along the west coast of Italy as far south as the Straits of Messina; and similar evidences are found on the shores of Tunis and Algeria.

[1] W. Howchin, *The Geology of South Australia*, Adelaide, 1918, p. 267.

Thus, as between the east and west coasts of Italy, we have a tilting movement in progress, the axis of which runs parallel with the peninsula. The Adriatic shores of Italy, however, are undergoing submergence.

The most recent uplift of which we have authentic evidence took place during the great Yakutat earthquake in Alaska, in September 1899, as the result of displacement along pre-existing fault-planes. The vertical uplift varied from 7 to 47 feet, as attested by the barnacles and bunches of mussel shells attached to the ledges of rock high above the present tide-mark.

Islands have undoubtedly disappeared from the Pacific as the result of seismic disturbances. As recently as 1910 one was engulfed off San Salvador, and over 200 of its inhabitants were drowned. Four years previously a mountain nearly 4000 feet high was thrown up on one of the Aleutian Islands, but disappeared again a few months later during an earthquake in Alaska.

The Bogoslof group, in the Behring Sea, is very subject to changes brought about by earthquakes and volcanic disturbances. One came into existence in 1883 during an earthquake, and a crater which crowned it continued smoking for seven years.

The most recent addition to the group occurred in 1906, when it was first seen and charted by an American whaler, and this also remained an active volcanic island for several years.

In October 1914, the Tologa Bay earthquake, New Zealand, brought down land-slips that blocked the course of the Uawa River, and overwhelmed the homes of some European settlers, causing loss of life.

Measurement of Earthquake Intensity.—The mechanical measurement of the amplitude of earthquakes is usually effected by *seismographs*[1] which are constructed so as to utilise the principle of inertia as exhibited in a horizontal pendulum, or in a suspended or finely-poised weight. They are capable of recording vibrations, however produced. For the recording of the more violent local earthquakes, the *seismometer*[2] is employed. It is less sensitive than the seismograph, but with some seismologists the names are interchangeable. The electrical seismograph devised by Prince Galitzin differs from the Milne in having its pendulum dead-beat, this being brought about by an arrangement of electro-magnets. The earthquake record is called a *seismogram*.

In the absence of instruments, the intensity of an earthquake is usually measured by its maximum effects, and in order to obtain data that will be of scientific value, these effects are given in terms of the *Rossi-Forel scale*, so named after the seismologists by whom it was formulated. Ten degrees of intensity are recognised according to the effects produced.

Rossi-Forel Scale of Intensity.	Absolute Scale.
I. Recorded by a single seismograph, or by several seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.	20
II. Recorded by seismographs of different kinds; felt by a small number of persons at rest.	40
III. Felt by several persons at rest; strong enough for the duration or the direction to be appreciable.	60
IV. Felt by persons in motion; disturbance of movable objects, doors, windows, cracking of ceilings.	80

[1] The seismograph designed by John Milne, Professor of Mining in the Imperial University of Tokio, is widely used for recording earthquakes.

[2] Gr. *seismos*=earthquake, and *metron*=a measure.

ROSSI-FOREL SCALE OF INTENSITY—*continued.*

	Absolute Scale.
V. Felt generally by everyone; disturbance of furniture and ringing of some bells.	110
VI. General awakening of those asleep; general ringing of bells, oscillation of chandeliers, stopping of clocks; visible disturbance of trees and shrubs. Some startled persons leave their dwellings.	150
VII. Overthrow of movable objects, fall of plaster, ringing of church bells, general panic, without damage to buildings.	300
VIII. Fall of chimneys, cracks in the walls of buildings.	500
IX. Partial or total destruction of some buildings.	1200
X. Great disasters, ruins, disturbance of strata, fissures in the earth's crust, rock-falls from mountains.	?

The average intensity of the earthquakes recorded in Japan is 81, and in New Zealand 78 millimetres per second per second, or a little less than degree IV. on the scale.

If the effects of a fairly sharp earthquake are carefully observed by a large number of persons we may be able to plot on a map the area within which many ordinary chimneys were thrown down (VIII.); then outside that area, another in which chimneys were not overthrown, but crockery and bottles were overturned (VII.); then a third area in which the shock was sufficient to stop a number of clocks (VI.); and so on. The lines bounding such areas are called *isoseismal* lines, or lines of equal earthquake intensity. The position and form of these lines will enable us to determine approximately the position of the centre of disturbance.

DIASTROPHISM.

Tilting of Strata.

Dip.—When a bed or stratum is tilted so as to be inclined in some direction, the *direction* of the inclination is called the dip; and it is always the steepest line of the inclined surface that shows the true direction of the dip.

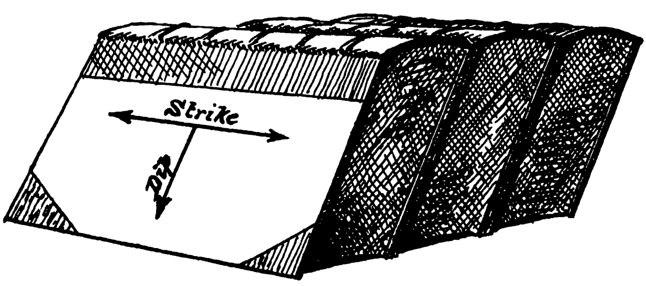


FIG. 64.—To illustrate dip and strike of strata.

The amount of the inclination, or the *angle of dip* as it is usually called, is always measured from the plane of the horizon.

Thus we have—

The direction of inclination = dip.

The amount of inclination=angle of dip measured from the plane of the horizon.

The *direction* as well as the *amount* of the dip is always observed and recorded. The direction of the dip is determined with a *compass*, and the amount of dip with a *clinometer*. The ordinary geological box-compass is provided with a pendulum-bob for recording angles of inclination on a graduated scale.

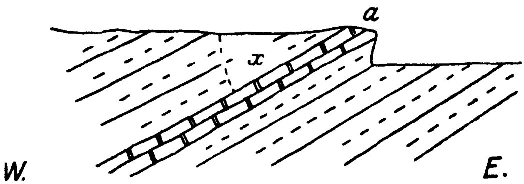


FIG. 65.—Showing angle of dip=x of the beds a.

The amount of the dip may vary from 0° to 90°. At 90° the beds are said to be *vertical*.

In fig. 65 the bed of limestone marked a dips to the *west* at an angle of inclination=x.

Strike.—The horizontal line along the tilted stratum is called the *strike*, and it is always at right angles to the dip (fig. 64).

In metalliferous mining the strike of a lode is commonly spoken of as the *course* of the lode. So that the horizontal direction pursued by the course of a lode or bed is the strike. If, for example, a seam of coal or a metalliferous lode crops out on a plain or level ridge, the line joining the various outcrops is the line of strike or course of the seam or lode.

If a tent-fly raised on a ridge-pole be taken to represent a folded stratum of rock, then the direction in which the ridge lies will represent the strike.

Furthermore, if the tent-fly represents an anticline, then the ridge is the *axis* of the anticline, as described on next page.

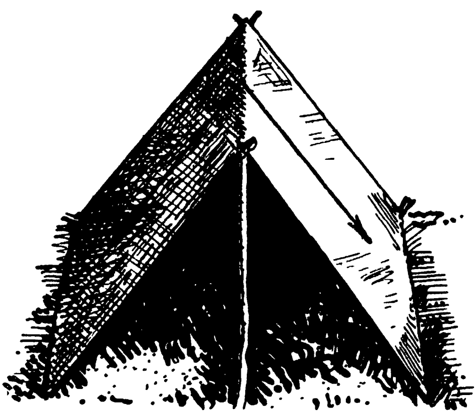


FIG. 66.—Tent-fly on ridge-pole, illustrating strike of strata.

The arrows indicate the dip of the limbs.

Folding of Strata.

The majority of sedimentary or clastic rocks were laid down as horizontal layers on the floor of some sea or lake. When, therefore, we find such rocks forming hills and high mountain-chains, we are compelled to conclude that they have been elevated by some powerful agency. And when on closer examination we find that these strata are not always horizontal, but in many places tilted and folded, we are further compelled to conclude that they have been subjected to enormous side-pressure.

It must always be borne in mind that although rocks are hard and resistant, they can be crumpled up and corrugated like a sheet of iron when sufficient lateral pressure is exerted on them.

The mechanics of the folding of strata can be illustrated in a graphic manner by the following simple experiment:—

Take fifty strips of cloth of different colours, about 2 feet long and 6 inches

wide, and pile them one over another on a flat table (fig. 67). The strips of cloth represent a series or succession of horizontal strata.

Next place a board on top of the pile and apply vertical pressure on the board. It will be observed that the horizontal position of the layers is not disturbed.

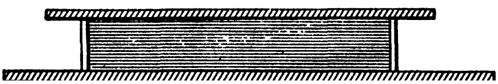


FIG. 67.—Showing pile of cloth.

Suppose, however, that we now place two on the board, and, holding a small piece of cardboard in each hand, apply pressure on the *ends* of the layers, slowly bringing our hands towards each other under the board. The cloth will now be found to be puckered up into a number of folds of various form and size. Moreover, the distance between the ends will be greatly diminished (fig. 68).

In this experiment we have a good example of what takes place when horizontal strata are folded. The lateral pressure throws the strata into folds, some of which may be gentle undulations, and others sharp corrugations according to the force exerted, the character of the rocks, and the pressure of the superincumbent strata.

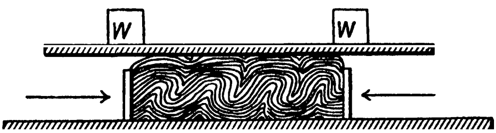


FIG. 68.—Showing pile of cloth folded by lateral pressure.

It is important to note that the strata when folded cover a smaller area than when lying horizontal.

In strata that have been deeply involved in folds it is not unusual to find the contained fossils and pebbles deformed, elongated, and even sheared in the direction of the lateral movement, which is sometimes called *lateral thrust.*

The folding and crumpling of strata are believed to be due to lateral pressure arising from the sinking of crustal segments upon the cooling and contracting interior.

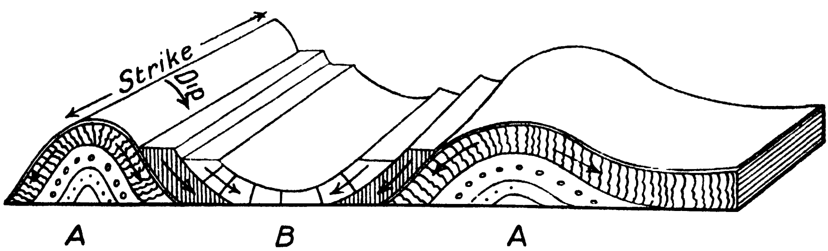


FIG. 69.—Showing folded strata.

A, Anticlines. *B*, Syncline.

Thus, when a block of horizontal strata is squeezed into a smaller segment the effect is to crumple the strata into folds.

The arch of a fold is termed an *anticline,*[1] and the trough a *syncline.*[2]

In a sheet of corrugated iron the ridges will represent *anticlines*, and the troughs *synclines.*

The line running along the crest of a ridge is called the axis of the ridge, *i.e.* the *anticlinal axis*, and the line along the bottom of a trough the *synclinal*

[1] Gr. *anti*=opposite, and *klino*=I incline.
[2] Gr. *syn*=together, and *klino*=I incline.

axis (fig. 69). For example, the ridge of a tent-fly supported by a ridge-pole is the axis of the roof (see fig. 66).

The sides of an anticline or of a syncline are called the *limbs*. In an anticline we speak of *arch-limbs* because they form the arch ; and in a syncline, of *trough-limbs* because they slope down so as to form a trough.

It is obvious that in the case of a syncline following an anticline, the adjacent

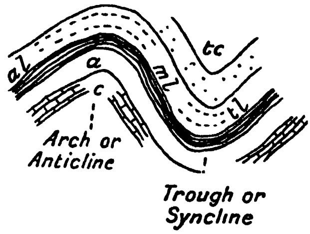


FIG. 70.—Diagram showing parts of a fold. (After Lapworth.)

(*ac*) Core of anticline. (*al*) Arch-limb.
(*tc*) Trough-core. (*tl*) Trough-limb.
(*ml*) Middle limb.

limb will belong to both, and is therefore called the middle limb, as shown in fig. 70.

Different Forms of Folds.—According to the character of the strata and the amount of compression, folds may assume different forms. The corrugations on a sheet of corrugated iron are *symmetrical*, but symmetrical folding is not very common in Nature. More frequently one side or limb of a fold is steeper

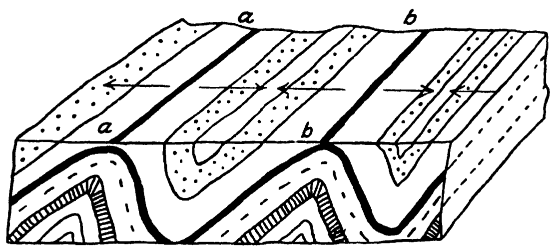


FIG. 71.—Showing folded strata in cross-section and plan.

(*a*, *b*) Outcrops of the seam of coal (in black) in the direction of the strike. The arrows are directed to the trough-cores.

than the other, and as this is the common type of fold, it is called *normal folding*.

In fig. 71 we have a series of beds, including a seam of coal arranged in two anticlines and two synclines, the folding being normal.

In cases of sharp folding, one limb may be vertical (fig. 72, *a*) or actually pushed over beyond the vertical (fig. 72, *b*). A turned-over fold is called an *overfold* or *inverted fold*.

When an overturned fold is pushed over so far that the limbs are parallel and nearly horizontal, we have what is termed a *recumbent fold*.

In what is termed a *monoclinal fold*, the strata are bent from the normal direction for a distance and then resume the original plane. In sharply bent monoclinals, the strata in the middle limb are usually drawn out, compressed, or deformed. In this way there are often formed the transitions from a fold

to a fault. Monoclinal folds generally are not formed by lateral pressure but by subsidence.

A notable example of monoclinal folding is seen in the Isle of Wight where,

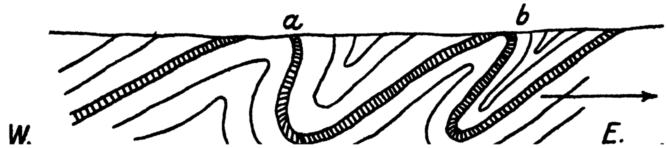


FIG. 72.—Section showing fold with vertical limb *a*, and overfold at *b*.

The arrow indicates the direction of the folding pressure.

on the south side of the island, the Cretaceous rocks are tilted till they are almost vertical, while the Lower Tertiary strata follow with a similar inclina-

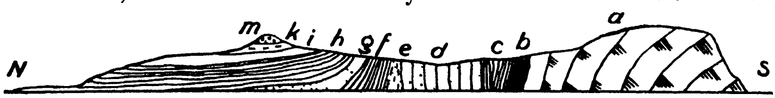


FIG. 73.—Showing *monoclinal* folding of Lower Tertiary strata in section of the Isle of Wight, Totland Bay to Headon Hill. (After H. W. Bristow.)

a. Chalk.—Cretaceous.
b. Reading Beds.
c. London Clay.
d. Lower Bagshot Beds.
e. Bracklesham Beds.
f. Barton Clay.
g. Barton Sands.
} Eocene.

h. Headon Beds.
i. Osborne Beds.
k. Bembridge and Hamstead Beds.
} Oligocene.
m. Gravels.—Recent.

tion, but rapidly flatten down, going northwards till they become horizontal on the north coast (fig. 73).

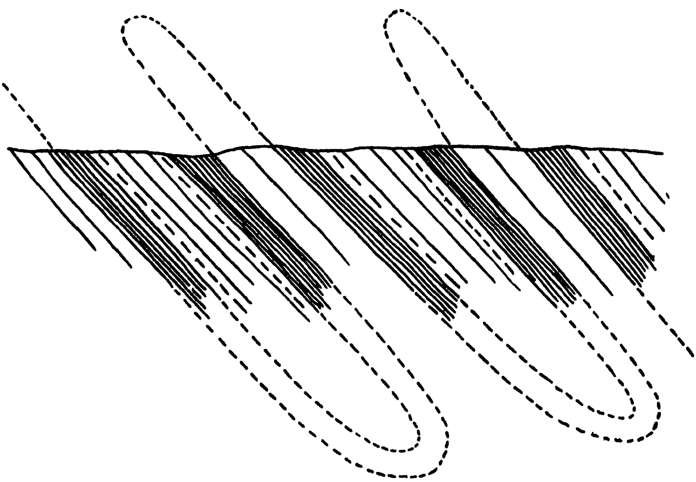


FIG. 74.—Showing *isoclinal* or *closed* folds.

A succession of closed overturned folds forms what is termed an *isoclinal.* Folds of this type (fig. 74) are frequently met with among the older schists and gneisses, and sometimes among Mesozoic rocks.

Strata that have been uplifted in the form of a *dome* so as to incline outwards in all directions, are said to have a *quaquaversal* dip.

In some central massifs of the Alps, the strata are arranged in a singular radial form, with great flanking corrugations. This is termed *fan-folding*, of the Alpine type (fig. 75).

Radial folding on a minor scale is sometimes seen in volcanic regions, arising from rapid local subsidence accompanied by lateral pressure.

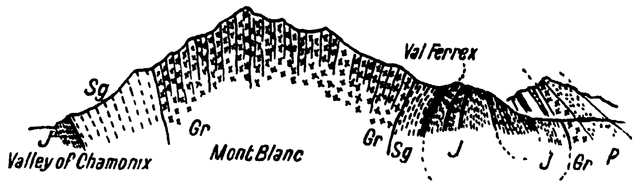


FIG. 75.—Section of Mont Blanc, showing fan-folding.
Gr, Granite. *Sg*, Gneiss and mica-schists. *P*, Quartz-porphyry. *J*, Jurassic.
(After A. Heim.)

Plication of Strata.—Plication is merely a form of minute folding. It is frequently seen among gneisses, mica-schist, and other metamorphic rocks that have been subjected to enormous lateral pressure. A great many plications are sometimes seen in the space of an inch.

Complicated plication has given rise to the term *contorted*, which is frequently applied to banded rocks that have been crumpled up into minute folds. Thus some gneisses and mica-schists are spoken of as *highly contorted*, which usually means that the rocks are finely plicated.

The hardest and most resistant rocks, under the influence of great stress, behave as semi-plastic bodies. In the process of folding, the limbs of the

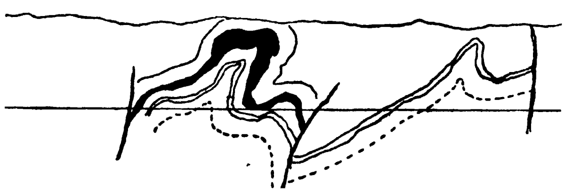


FIG. 76.—Showing thinning of coal-seam due to contortion of coal-measures in the Saint Eloy Basin, France. (After De Launay.)

plications are frequently found to have been squeezed till they have become thin. Where this has happened, the crests and troughs of the folds usually show a corresponding thickening, the flowage being from the region of greatest stress in the limbs to the places of least stress in the arches and troughs (fig. 76). The hardest mineral substances, even quartz, seem to be capable of flowage under the influence of sufficient pressure.

Shales, sandstones, and nearly all sedimentary rocks exhibit the same thinning in the limbs of sharp folds due (*a*) to compression and consolidation of the constituents, or (*b*) to the elongation arising from the shearing which has so frequently accompanied sharp folding and crumpling of the strata.

Overthrusts.—In the Alps of Europe there is a large zone that is built up by recumbent folds of very large dimensions. These folds are refolded and their anticlines, in part, dive downwards (fig. 77). There are transitions from these overthrust folds to overthrust masses, that are separated from their substratum by a thrust plane. These overthrusts originate from the shearing

of recumbent folds, whose middle limb is destroyed by the movement of the hanging limb (fig. 77A) or changed into a mylonite, *i.e.* a contorted and laminated rock, frequently found at the base of overthrust blocks. The Alps of Switzerland are built up by such overthrust masses, which by erosion are more or less

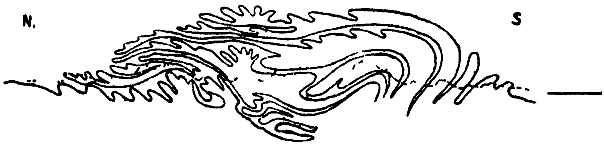


FIG. 77.—Section through the Swiss Alps, showing overthrust folds, as originally formed. The dotted line marks the surface of to-day. (After A. Heim.)

dismembered and often separated from their posterior (southern) pieces, which are called *roots*.

The mechanics of the formation of overthrust folds are not clearly understood. The existence of a resistant zone, towards which the folds are pushed, seems to explain the development of the overthrusts. In the Alps many great masses of strata have been carried bodily by thrust to a great distance from the parent site.

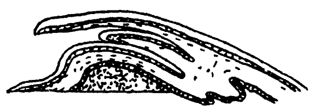


FIG. 77A.—Recumbent folds passing into thrust-masses. (After A. Heim.)

There seems to be a second class of overthrust, not originating from folds, but consisting of masses, which are moved along thrust-planes, splitting the Earth's crust at a low angle. To this type probably belong the great thrusts of the North-Western Highlands of Scotland, admirably exposed in the Zone of Eriboll, and the thrusts of the mountain-chain of Scandinavia.

Outcrop.—The edges of strata which appear at the surface are called the *outcrop*. The exposed edges of hard resistant rocks sometimes form conspicuous escarpments that can be traced for many miles.

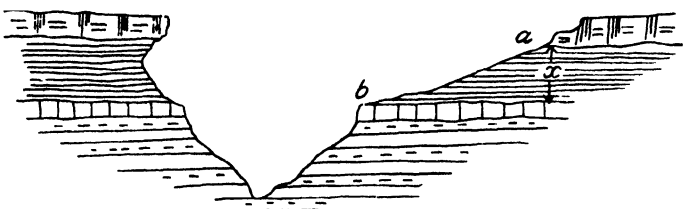


FIG. 78.—Showing outcrop of horizontal strata in a gorge.

When the strata are horizontal, the outcrop of the different beds will only be seen in a sea-cliff, valley, or gorge.

On sloping ground the extent of the outcrop does not represent the true thickness of the beds. For example, in fig. 78 the thickness of the bed lying between the two bands of limestone is not *a*-*b*, but the line *x* at right angles to the plane of the bed.

Outcrop Sag or Curvature.—In dissected areas, weak rocks, such as mica-schist and shales, are frequently found to be bent or curved at the outcrop. This sag sometimes renders it difficult to obtain trustworthy observations as to the true dip of the strata. It is caused by the drag or sag of the outcrop

ends of the beds arising from the stress due to their own weight (fig. 79), and is often met with in deep gorges or steep mountain slopes.

In regions that were at one time covered with a thick sheet of ice, it is not uncommon to find weak rocks bent, or even crumpled up and shattered, for many yards below the surface.

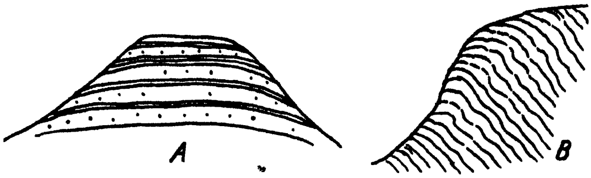


FIG. 79.—Showing effects of outcrop sag of strata.
A, In horizontal beds. *B*, In tilted beds.

In a series of strata containing a bed of limestone, the underground solution and removal of the calcareous rock may cause unequal settlement of the overlying beds over a considerable area, whereby a *false dip* is presented to the observer.

Denudation of Folds.—Many beds that have been folded do not, as we now

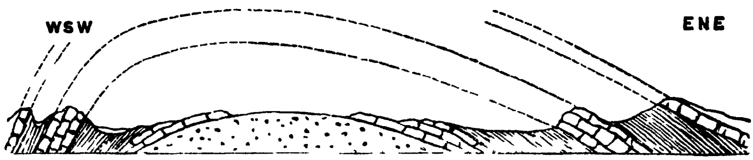


FIG. 80.—Showing denuded crown of anticlinal fold of Silurian rocks in the Valley of Woolhope, Herefordshire.

see them exposed at the surface, show complete anticlines and synclines. In most cases the crowns or crests of the folds have been removed by denudation, so that it is only by plotting the dip and strike of the different outcrops that we are able to tell that the folds exist.

It is probable that the folding of the strata and denudation proceeded at

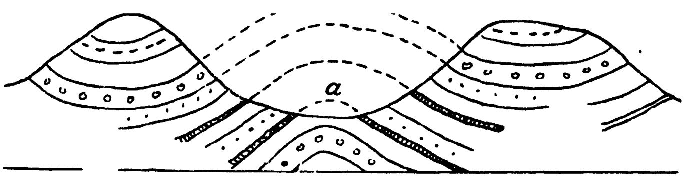


FIG. 81. Showing valley excavated along course of an anticline, and ridges composed of beds arranged in synclinal folds.

the same time. In this case the crown of the fold would be worn away in such a manner that the complete arch, as indicated by the dotted lines in fig. 80, probably never existed.

It is not often that the apex of an anticline is seen, except in the case of small folds.

Strata arranged in the form of an anticline will be worn away faster than the same beds disposed in the form of a syncline. In the anticlinal arrangement the limbs dip away from one another, which permits the rain to find its way readily along the bedding planes, where it disintegrates the rock, thereby

assisting the force of gravity in breaking up the outcrops. The rain-water lying between the bedding planes by its hydraulic pressure also exerts a strong disruptive force which, in cold climates, will receive effective help from frost.

In the case of the synclinal arrangement, the limbs dip towards one another, the different beds resting on each other like a pile of saucers. The beds thus support one another, and consequently their exposed edges alone are subject to the effects of denudation.

Hence, we frequently find that the valleys have been excavated along the course or axis of anticlines, while in the adjacent ridges the beds are arranged in synclinal folds as shown in fig. 81.

Outliers and Inliers.—These commonly arise from the denudation of horizontal or gently undulating strata. Many formations that at one time formed a continuous sheet over extensive areas have been greatly reduced in size, and in some cases they are now represented by only a few interrupted sheets and isolated patches.

A notable example of the gradual destruction of a formation is exhibited by the *Desert Sandstone* which at one time covered over 400,000 square miles of the surface of Queensland, but has now been worn away to about a twentieth

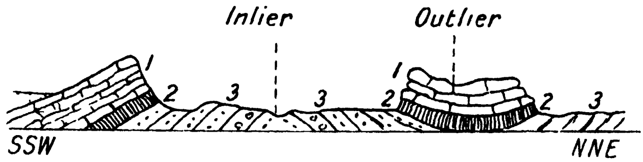


FIG. 82.—Section along west side of Weka Pass, N.Z., showing outlier and inlier.

(1) Weka Pass stone. (2) Amuri limestone. (3) Greensands.

of its former extent, and is represented only as a series of isolated ridges, peaks, plateaux, and *mesas* [1] scattered over the interior.

An *outlier* is simply an isolated remnant of more extensive beds, and is usually defined as a detached mass of rock *surrounded* on all sides by *older* rock.

Outliers occur among all kinds of rock, including loose gravel. The beds forming them may be horizontal, inclined, or folded. Examples are frequently met with in front of prominent escarpments of limestone and basalt.

Outliers of Jurassic and Cretaceous strata are common in Central England. Table-topped outlines of basalt are numerous in India and Victoria, and in all countries where dissected sheets of basaltic lava cover the ancient plateaux.

An *inlier* is the converse of an outlier. It consists of an isolated mass of rock on all sides *surrounded* by *younger* rocks. An inlier is the result of denudation, hence most frequently met with in valleys, or in places where the arch of an anticline has been partially worn away.

An example of an inlier is seen at the point marked *a* in fig. 81.

Crustal Folding and Mountain-Building.—All the principal mountain-chains on the planet owe their existence to the uprising of crustal folds, and mountain-making may be defined as the result of localised folding in regions where the uplift is faster than the rate of denudation. If the rate of denudation were equal to the rate of uplift, it is obvious that the truncated and dissected folds would never form highlands or features of bold relief. A potential mountain-making fold suppressed by denudation would in time become buried in the

[1] Span. *Mesa*=a table.

waste derived from its own destruction, and the ultimate result would be a worn-down stump indistinguishable from the stump of an alpine chain worn down by long-continued subaerial denudation.

Alpine chains may therefore be regarded as the expression of relatively rapid folding.

It is seldom that a mountain-chain consists of a simple anticlinal fold. More often the great chains consist of a series of deeply dissected isoclinal folds forming a confused alpine complex, flanked by many more or less parallel ranges. The great height and rugged contours of the Pyrenees, Alps, Himalayas, Andes, and Rocky Mountains are an evidence of their comparative youth. Their uplift has been so recent and rapid, that denudation has merely succeeded in eroding the crests of the folds into narrow serrated ridges, deep valleys, and profound gorges.

There is evidence that great alpine chains existed in the remotest geological ages. All of these chains were vigorously attacked by the contemporary agents of denudation, their waste furnishing the sediments that built up the later formations. The only vestige that remains of these primitive alps is their worn-down stumps, many of which have lain for countless æons buried beneath piles of sedimentary strata. Here and there the buried stumps have become exposed by recent denudation, or disclosed by deep boring.

When a renaissance of the folding movements takes place along the segment occupied by a worn-down and buried alpine chain, a second alpine chain may rise on the ruins of the first. Most of the existing mountain-chains occupy the ruins of Palæozoic chains, the stumps of which have sometimes become involved in the later folds.

In the complex structure of Europe, Lapworth and Suess have recognised four primary folded chains all overfolded towards the north, namely—

(1) The **Caledonian,** a pre-Devonian S.W.-N.E. folding.
(2) The **Armorican,** a pre-Permian W.N.W.-E.S.E. folding.
(3) The **Variscan,** a pre-Permian W.S.W.-E.N.E. folding.
(4) The **Alpine,** an early Cainozoic folding that formed the existing alpine chains.

The Caledonian is the northernmost of these ancient alpine chains. It is composed of a massif of Archæan granites, gneisses, schists, and older Palæozoic slates, sandstones, and quartzites that extend from the west of Scotland north-eastward to the northern limits of Scandinavia. It causes little surprise to find that rocks of such antiquity have been crushed into many complex folds, overthrust, and profoundly faulted.

The great Caledonian disturbances are well expressed in the "Zone of Eriboll" in the North-Western Highlands of Scotland [1] and at the eastern margin of the high mountain-chain of Scandinavia, which is accompanied by a large overthrust directed to the east, while the overthrust in the Zone of Eriboll has a westerly direction.

The Armorican is a zone of intense folding, so named from the ancient name of Brittany. It is the result of movements that ridged up the Carboniferous and earlier formations of Western and Central Europe, sometime between the close of the Early Carboniferous and the advent of the Permian. At the close of the Palæozoic it was the most prominent geographical feature in Western Europe. The truncated remains of this ancient chain can still be

[1] "The Geological Structure of the North-West Highlands of Scotland," *Mem. Geol. Surv. Great Britain,* 1907.

traced from Ireland to Central France, in part buried beneath a pile of Mesozoic and younger formations.

The Variscan [1] Chain takes its origin in the Central Plateau of France, where it is linked with the Armorican Chain, and whence it stretches in a north-easterly direction to the Rhine. It has been broken into numerous blocks, and though there are now only isolated fragments remaining at the surface large portions of this ancient chain still exist, covered by a thick sheet of younger strata. Among the higher exposed portions are the Vosges, the Black Forest, the Odenwald, the Rhenish Mountains, which are traversed by the Cañon of the Rhine from Bingen to Bonn, the Harz, the Thuringian Forest, the Erzgebirge. In the north-eastern Erzgebirge the strike of the folds passes into a south-easterly one, which predominates in the Silesian Mountains, finally bending in the old direction N.E.-S.W. All parts of the Variscan Chain are not of exactly the same age, the folding processes having begun at the beginning of the Carboniferous, and reached its maximum at the end of the Lower Carboniferous. At the northern margin the coal-measures of Westphalia, which are of Upper Carboniferous age, were folded towards the close of the Upper Carboniferous, and in several regions there were important movements as late as the Permian age.

Collectively the Armorican and Variscan chains are called the **Hercynian** system, the name being derived from the " Hercynian Forest," the ancient name of the mountains of central Germany.

The Alpine folding lies south of the Hercynian, and extends from the Atlantic border to the Black Sea, and includes the Pyrenees, Alps, Carpathians, Balkan Mountains, the Dinarides, Apennines, Sicilia, and the Atlas.

These ancient diastrophic movements caused intense crustal deformation that resulted in the catastrophic ruin of existing geographical units and the birth of new continents. The redistribution of the great oceans arising from these movements is believed to have brought about climatic changes that profoundly influenced the development of life.

The diastrophic foldings were accompanied by magmatic intrusions that originated the series of after-eruptive processes by which many valuable ore-deposits were formed, That is, the chief ore-forming periods were the Devonian, pre-Permian, and early Cainozoic.

The periods of intense crustal deformation alternated with long intervals of relative quiescence that were distinguished by the accumulation of great thicknesses of sediments along the borders of the continents.

In the American continents, the Pacific Ocean is bordered by high mountain-chains that are surmounted by many active and extinct volcanoes. These are typical folded chains of the meridional type, that turn their folds towards the abysses of the sea. The segment of the Aleutian Islands forms an independent fold.

It is significant that all the great chains of Europe, Asia, and North Africa, with the exception of the Urals, are composed of east and west folds ; while the Andes, Rocky Mountains, and Sierras in America, as well as the mountain-chains of Australia and New Zealand, run parallel with arcs of the meridian.

Volcanic activity is frequently associated with areas of vertical displacement resulting from faulting or intense folding ; and all great earthquakes are the jolts propagated by the revival of movement along ancient, but in most cases well-defined, fault-lines.

[1] So named after Curia Variscorum, the ancient name of the town Hof in the Fichtelgebirge (Germany).

SUMMARY.

Elevation.—(1) The occurrence of rocks containing marine shells at a height above sea-level is an evidence of elevation of the land in past geological times. The existence of raised beaches or sea-strands is a proof of comparatively recent elevation.

Subsidence.—(2) The best proofs of subsidence are submerged forests and coal-seams, drowned valleys, and atolls.

The forests grew on the dry land near the sea, and could only become submerged by the sinking of the coastal region. Likewise coal-seams are composed of the remains of a terrestrial vegetation that required air and sunlight for its growth. Therefore, when seams are found thousands of feet below sea-level, we know that subsidence to that extent has taken place.

The fiords of Norway and New Zealand are merely submerged mountain-valleys. In California and elsewhere some of the existing river-valleys can be traced by soundings far seaward of the present shore-line—clearly a proof of subsidence in quite recent times.

According to the view of Darwin, atolls and barrier reefs were formed by the upward growth of the coral-building polyp on a slowly sinking sea-floor. The borings at Funafuti showed the existence of coralline and foraminifera limestones at a depth of 1114·5 feet below sea-level; and since the coral polyp cannot live in water deeper than say 150 feet, a subsidence of over 800 feet must have taken place in that area.

(3) Rapid earth-movement may be due to volcanic eruptions or to the sudden jolts arising from earthquakes.

Tilting of Strata.—(4) The direction in which a stratum or bed is inclined is called the *dip*; and the amount of the inclination measured from the plane of the horizon is the *angle of dip*.

The *strike* is the horizontal line along the tilted stratum, and it is always at right angles to the dip.

Folding of Strata.—(5) The majority of sedimentary or aqueous rocks were laid down in a horizontal position, but many of them have since been pushed into folds by lateral pressure that in all probability arose from the cooling and contracting of the Earth's crust.

The arches of folds are called *anticlines*, and the troughs, *synclines*. Simple symmetrical folding is rare. More commonly the folds are unsymmetrical, the limbs being shorter and steeper on one side than on the other.

Folds that have been subjected to great lateral pressure from one direction are sometimes pushed over and form what are called *overturned* or *inverted* folds. When an overturned fold is pushed over until the limbs are closed and nearly horizontal it is called a *recumbent* fold.

Most *overthrusts* arise from an exaggeration of folding, and originate from recumbent folds that have been broken by shearing of the median limb. A mass moved by an overthrust is a *thrust-mass*. Large thrust-masses occur in the Alps, where they have been described by Heim, Schardt, etc.

A succession of closed folds that are overturned, but not recumbent, form an *isoclinal*.

Great anticlinal arches with minor corrugations on the flanks are called *geanticlinals*, and great troughs, *geosynclinals*. In the Alps of Switzerland the crystalline massifs of Mont Blanc, Gotthard, etc., form large fan-like anticlines with a radial arrangement of the strata.

Plication of Strata.—(6) Plication is a form of minute folding frequently seen among the older altered rocks, such as gneiss and mica-schist. Plication

may be very complicated. Rocks that are strongly plicated are frequently spoken of as *contorted*. Contorted schists sometimes exhibit a thinning or drawing out of the limbs of the folds with a corresponding increase in the arches and troughs. This indicates that a certain flowage of the rock-constituents took place under the stress of enormous pressure. In other words, under great pressure the rock-constituents behave as plastic bodies.

Shearing.—(7) When rocks are subjected to a travelling lateral pressure that is arrested by some resistant massif, they are frequently forced into sharp overturned folds which may become fractured and sheared, the upper portion of the fold being pushed over the lower. This *overthrusting* of crustal segments has been observed in the Highlands of Scotland by Peach. Shearing that has not been preceded by folding is rare.

Outcrop.—(8) The edges of strata that appear at the surface are called the *outcrop*. Weak rocks may be bent or curved at the outcrop by the weight of their own mass or by the stress of a sheet of moving ice. Such *outcrop curvature*, as it is called, is common in shales, phyllite, and mica-schist.

Denudation of Folds.—(9) The majority of folds of considerable size have been denuded to a greater or less extent; hence their existence is usually deduced by construction from the observed dips and strikes as recorded in the field.

(10) *Outliers* are the isolated remnants of a rock-formation that at one time formed a continuous sheet over an extensive area. They may be defined as detached masses of rock surrounded on all sides by older rock.

An *inlier* is the converse of an outlier. It consists of an isolated patch of rock surrounded on all sides by younger rock. Hence inliers are most frequently found in the exposed crowns of anticlines.

Crustal Folding and Mountain-Building.—(11) Mountain-chains are composed of great uplifted crustal folds that have been deeply dissected during the progress of the uplift.

CHAPTER XI.

JOINTS, FAULTS, CLEAVAGE.

Joints.

Joint Structure.—Joints are simple cracks or fissures. They are found in rocks of all kinds and of all ages.

Sedimentary rocks are usually traversed by two systems or sets of joints, both perpendicular to the stratification planes, and commonly intersecting one another at right angles. The joints in each set are approximately parallel to one another.

As a rule, one set of joints is more pronounced than the other, and may be traced for many yards. The joints in the major set are commonly called *master-joints*.

The course of the master-joints is usually parallel with the strike of the main lines of uplift; that is, parallel with the axes of the anticlines.

The two sets of joints and the bedding planes give three planes nearly at right angles, which divide the rock into cuboidal or prismatic blocks and columns.

Rocks that have been much disturbed are sometimes intersected with three or four systems of joints. Generally speaking, rigid rock is more jointed than one that is more yielding.

The joints in each set may be many feet or yards apart, or in exceptional cases only an inch or less.

In horizontal strata, the joints are usually approximately vertical; but in regions where the rocks have been subject to great disturbance, the joint planes may occupy any position.

Joints are sometimes mistaken for bedding planes, but these can usually be distinguished by lines of material of different texture or colour, or by lines of nodules and hard bands, or by fossils arranged in bands parallel with the bedding planes.

Joints are of necessity confined to the zone of fracture; and in the majority of cases, an individual joint when followed along its course seems to die out in less than a score of yards, to be succeeded after a longer or shorter interval by another joint following the same general direction.

Many joints end at the contact of two kinds of rock, but *master-joints* may pass through a whole series of rocks. For example, throughout the whole of Yorkshire the Mountain Limestone Series is traversed by master-joints passing downward through the limestone, sandstone, and shale in nearly the same direction (fig. 83).

Joints are more or less open, or usually filled with silt and mud carried into them by water. In many cases, more especially in limestones and other calcareous rocks, they have been enlarged into gaping fissures or caves by the

action of underground waters. On the surface they frequently become enlarged through the solvent effect of rain, aided by the ordinary processes of weathering.

Joint planes sometimes show polished and grooved surfaces, which would tend to show that a certain amount of sliding movement had taken place parallel to the polished faces. Evidence of displacement along joint planes is perhaps exceptional.

The majority of the older coal-seams are traversed by two sets of vertical joints called *cleats*, crossing one another at right angles. The *face cleats* run parallel with the strike of the seam and are usually the more pronounced. The *end* or *butt cleats* are shorter and not as a rule so well defined.

The *cleats* are of great importance in facilitating the getting of the coal; hence the direction of the working faces or breasts with reference to the *cleats* is a matter of supreme importance.

The joints in igneous rocks are not generally so regular or well defined as in sedimentaries. But in exceptional cases they are so symmetrically disposed as to produce the well-known prismatic columnar structure which is sometimes seen in flows of basaltic rock, and less often in andesites, trachytes, and rhyolites.

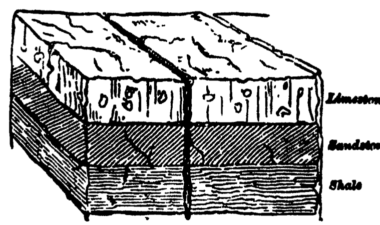


FIG. 83.—Showing master-joints passing through different rocks.

Granite is frequently intersected with two sets of joints, one of which is sometimes well defined. When the joints are far apart, large blocks of stone can be obtained, but when they are close together, the rock is broken up into a rubble of small fragments.

The master-joints, in whatever rock they occur, are always utilised by the workmen to facilitate the hewing of the stone in blocks that can be turned to commercial account.

In the joint planes in hard rock there are often found moss or fern-like markings that are sometimes mistaken for fossil ferns. These markings are formed by the infiltration of water containing iron or manganese salt in solution. They are called *dendritic* [1] markings. They occur also on bedding-planes.

Causes of Jointing.—The mechanics of jointing has not yet been satisfactorily explained, although many suggestions have been advanced by different writers. The generally accepted opinion is that the joint-cracks are the result of the various stresses connected with the contraction and folding of rock-masses.

Among the stresses referred to are *shrinkage* arising from the drying, or cooling of the rock, *tension* and *shearing* due to folding.

Thick sheets of mud when drying in the sun develop vertical cracks due to the dehydration and contraction of the mass. Sheets of lava in the portions exposed to the cooling effects of the atmosphere or of the surface on which they rest, as they cool also develop well-defined cracks that only in exceptional cases show the symmetrical arrangement known as columnar structure.

In sedimentary rocks the *master-joints* may pass downward through different kinds of rock; and in passing through a conglomerate may even sever the constituent pebbles in two. Clearly, then, the jointage in these cases took place after the consolidation of the rocks.

The orientation or general direction of the *master-joints* in clastic rocks is

[1] Gr. *dendron*=a tree.

usually parallel with the axes of the folds, which would lead us to the conclusion that it was in some way genetically connected with the processes or mechanics of folding. It would seem as if the stresses arising from the bending of the hardened and rigid rock-mass were relieved by the formation of innumerable short cracks or rents running parallel with the main line of uplift; that is, parallel with the strike. In other words, when the bending exceeded the elastic limit of the rock, parallel fractures were formed.

But anticlinal folds have a beginning and an end. Some may be short and plunge steeply at the ends. Others may extend for scores or even hundreds of miles before they die out.

The formation of an anticlinal fold can be best understood by reference to a simple experiment. Suppose, for example, that we place a long pillow or bolster lengthwise on a table and over it throw a sheet or table-cloth.

It will at once be seen that the anticline of cloth rises gradually from one end of the table till it becomes well defined along the body of the pillow; and at the other end plunges or *pitches*, as it is called, until it finally dies out as the horizontal surface of the table is reached.

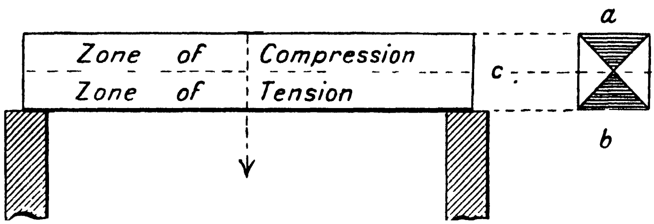


FIG. 84.—Showing distribution of stresses in a loaded beam.

By a similar experiment with two pillows and a sheet it can be shown that synclines also have a beginning and an end.

Let us now suppose that the table-cloth is replaced with a sheet of hardened rock bent into a simple fold. It is obvious that the greatest bending stress will be exerted parallel to the axis of the anticlinal uplift. If the rock is rigid and refuses to bend easily, the stress will be relieved by the formation of *master-joints* running parallel with the strike or axis of the fold. These joints will be *tension-cracks*, developed in the tension-zone.

There will also be a tensional stress at the ends of the folds due to the extension of the strata as it rises from the horizontal position. This stress will not be so great as that parallel with the axis, and as a consequence it will be relieved by the formation of smaller and shorter joints.

Joints formed by anticlinal folding are obviously the result of tension in the *upper* layers of the uplifted mass; while those arising from synclinal folding are the result of tension in the *lower* layers, in accordance with a well-known law in mechanics.

For example, if we take a beam of wood, supported at both ends and loaded at the centre, the upper layers will be in compression and the lower in tension, as shown in fig. 84.

The portion of the beam lying above the *neutral axis* or line of no stress, *c c*, will be in *compression*, and the portion below the neutral axis in *tension*. The magnitude of the stresses is greatest at the upper and lower surfaces of the beam, and diminishes as the neutral axis is approached, as graphically shown by the shaded portions of the stress diagram at *a* and *b* (fig. 84).

If the force were applied from below so as to cause upward bending, or a tendency to bend, the upper layers would obviously be in tension and the lower in compression.

Now, bending in any direction is always accompanied by a *horizontal shearing stress*, although in a homogeneous beam or mass this stress is not always obvious. But its existence can easily be proved experimentally.

If we replace the solid beam with a pile of thin boards, supported at both ends and loaded with a weight *W* at the centre, the boards will not only be bent, but they will also slide over one another as a result of the horizontal shearing stress, as shown in fig. 85.

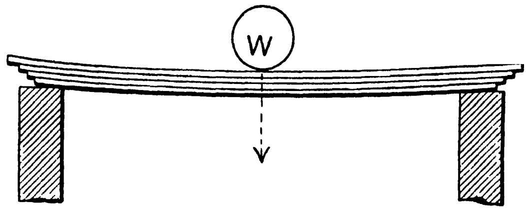


FIG. 85.—Showing effect of a horizontal shearing stress.

Stratified rocks that have been sharply folded frequently exhibit evidence that slipping or shearing has taken place along the bedding planes during the process of folding. The presence of a layer of clay, as well as grooves and striæ on the bedding-plane surfaces, are among the most obvious of these evidences. In cases where the shearing stress cannot be relieved by the movement of the beds, relief may be found by the formation of joints or cracks at right angles to the line of force.

The jointing of rocks may, therefore, be set down mainly to the influence of tension and shearing resulting from crustal disturbance, sometimes supplemented by the stresses introduced into rock-masses by shrinkage during the processes of drying and cooling.

Faults.

A crack or rent without movement of the rock on either wall is a simple fracture. In the majority of large cracks there has not only been fracture, but also displacement. In other words, the rents have become what are known to geologists and miners as *faults*.

Definition of Fault.—A fault may be defined as a fracture, on one side of which movement has taken place, whereby the rocks on that side have been displaced relatively to those on the other side.

Origin of Faults.—Faults are caused by crustal stresses arising from the slow secular folding movements that build up mountain-chains, or from the sharper movements propagated by the intrusion of igneous magmas or by earthquakes. That is, the disturbing agents may be *orogenic* or *hypogenic*.[1]

A fault may be the result of a single continuous movement, slow or fast, or of a succession of slight movements, with intervals of quiescence. The renaissance of movement on an ancient fault-plane may be responsible for the production of earthquakes and other seismic phenomena.

In regions where the rocks have not undergone much disturbance, but approximately occupy the original position in which they were laid down, faults are probably due to mere subsidence of crustal blocks, arising from the action of *vertical shearing stress*. In a loaded beam this stress tends to fracture the beam in a vertical direction (fig. 85A), and in every crustal segment there must be the same tendency. When the stress exceeds the ultimate strength of

[1] Gr. *hypo*=under, and *genesis*=production.

the rocks composing the segment, fractures will be formed, producing the effect known as step-faulting, shown in fig. 100.

Coal-mining operations have shown that the coal-measures in most lands are intersected by numerous faults, and it is probable that all portions of the Earth's crust are dislocated in the same way.

Many, if not the majority, of the great faults that traverse the crust seem to be connected with folding and mountain-building. They are frequently zones of dislocation or *thrust-planes* rather than true faults.

Along the course of thrust-planes, sometimes called *shear-planes*, the rocks are usually crushed and shattered, and the zone of crushed rock may be many yards wide. *Shear-zones* have often become mineralised by the infiltration of metal-bearing waters.

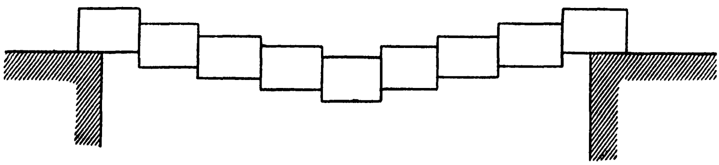


FIG. 85A.—Showing effect of vertical shear.

The inclination of faults, measured from the horizon, is generally high, being in most cases over 40°. The inclination of thrust-planes, on the other hand, is, as a rule, quite low, seldom exceeding an angle of 20°. This seems to be a consequence of their origin, for it is only when the folds have been thrust into a nearly recumbent position that fracture and shearing take place.

Relationship of Faults and Joints.—Joints may be taken as the expression of the internal stresses arising in disturbed rock masses ; and faults as the expression of the rupture by which crustal folds achieve relief when the stress exceeds the limit of relief afforded by joints.

Therefore, while joints and faults are essentially different, they can both be traced to the same cause, and in this respect they may be said to have a close genetic relationship.

Relationship of Faults and Folding.—The stress of sharp folding is frequently relieved by the formation of powerful fractures which by movement or shearing may develop into faults. In fig. 86 we have an example of folding without

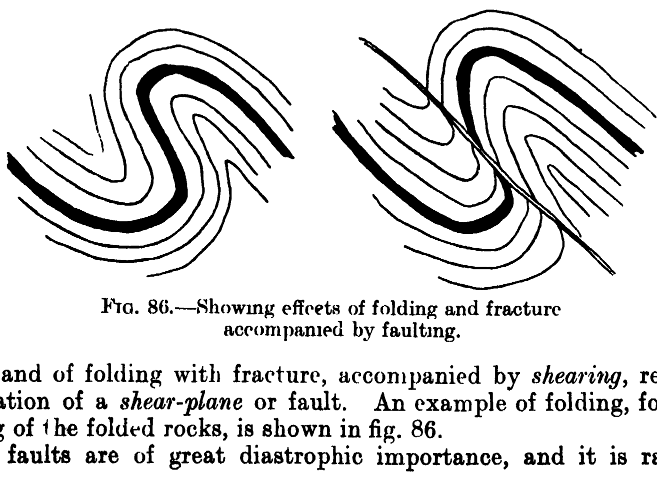


FIG. 86.—Showing effects of folding and fracture accompanied by faulting.

fracture, and of folding with fracture, accompanied by *shearing*, resulting in the formation of a *shear-plane* or fault. An example of folding, followed by fracturing of the folded rocks, is shown in fig. 86.

Many faults are of great diastrophic importance, and it is rarely that

intense folding and mountain-building has been unaccompanied by shearing and faulting. Among notable faults are the Caledonian Glen of Scotland, the Great Rift in Central East Africa, and the Block Mountains of Central Otago. Some faults have caused a vertical displacement of many thousand feet.

Linear Extent of Faults.—Faults, like joints, have a beginning and an end. They begin gradually, attain a maximum, and then gradually die out. Many of the small faults met with in mining regions are short, frequently less than a hundred yards long. Some large faults, however, can be traced for scores of miles. Many faults are cut off by other faults.

The course of large faults is usually more or less sinuous, and some fault-faces exhibit many minor corrugations.

Evidences of Faulting.—The opposing walls or surfaces of a fault-plane are usually polished, scratched, and grooved by the rubbing which took place when they moved against one another. Such polished and striated surfaces are called *slickensides*.

In many cases the fault-fissure is filled with crushed rock fragments, or lined with a layer of clay which is known to miners as *pug*. This clay is merely

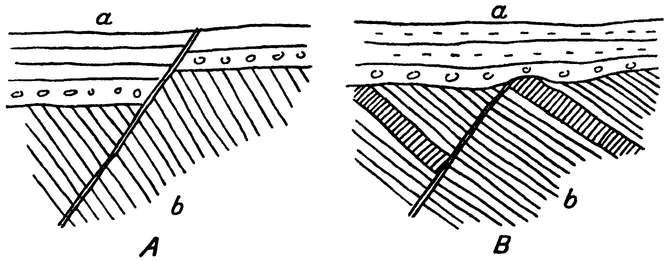


Fig. 87.—To illustrate age of faults.

A, Where faulting took place after deposition of beds *a*.
B, Where faulting took place before deposition of beds *a*.
(*a*) Miocene beds. (*b*) Cretaceous beds.

rock-flour, formed by the attrition of the rock-surfaces upon one another, and it may be plastic, or so hard as to resemble a slaty shale.

In powerful faults in which great movement has taken place, the wall-rock may be crushed and *brecciated*—that is, broken into angular fragments—for a width of many yards. The plane of the Moanatairari Fault which intersects the Thames Goldfield is in places occupied by a zone of crushed rock and soft clay, varying from 40 to 100 feet wide.

Many fault-fractures became channels for the circulation of mineralised waters, which deposited in them quartz or other crystalline minerals together with ores of economic value. It was in this way that many of the most valuable ore-veins were formed.

Age of Faults.—A fault is obviously younger than the rocks that it intersects, and when the rocks are traversed by two systems of faults, one system will usually be found to displace the other, thereby affording conclusive evidence that it is the younger.

A fault that traverses, for example, a pile of Cretaceous and Miocene strata must be younger than Miocene (fig. 87, *A*). If the Miocene beds are overlain by Glacial Drift which is not disturbed by the fault, then the date of faulting took place some time *after* the Miocene, and *before* the advent of the Glacial Period.

Or again, if the fault traverses the Cretaceous beds and not the overlying

Miocene, as in fig. 87 (*B*), then we know that the fault is younger than Cretaceous, but older than Miocene.

Movement is believed to be still in progress along the planes of some of the great faults of late Tertiary date. The joltings caused by the sudden settlement of the ground on the downthrown side of the San Juan fault are held by some to have been responsible for the disastrous earthquakes that ruined San Francisco in 1906.

Fault-Structure.—Faults intersect rocks of all kinds and all ages. Some of them are crustal dislocations of such magnitude that they can be traced on the surface for scores and even hundreds of miles.

Faults may run in any direction, but the major faults of a region frequently possess the same general bearing.

A fault may run parallel with the strike of a bed or lode, or it may cross the strike at right angles or at any other angle.

Some regions are intersected by a number of parallel faults, and in some places two or more independent systems of faults may mutually intersect one another.

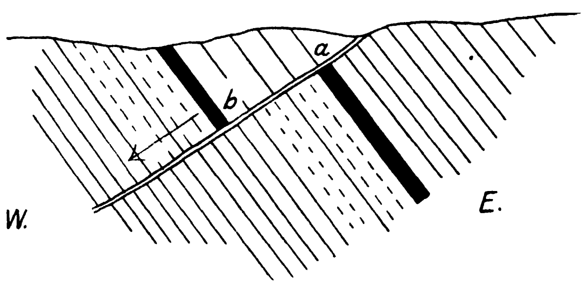


FIG. 88.—Cross-section showing direction of downthrow in normal fault.

Hade of Faults.—Faults are not often vertical, but usually incline to one side or the other. A fault is said to *hade* when it inclines from the vertical plane. The *hade* of a fault is, therefore, the angle which the fault makes with the vertical plane. *Hade* and angle of *dip* are thus only the same when both are 45°.

The hade-line of a fault is the resultant of two principal component forces, namely, gravitational stress acting vertically towards the centre of the Earth, and lateral thrust mainly due to subsidence.

Classification of Faults.—Faults, according to the direction of the vertical displacement, are divided into two classes, namely—

(*a*) *Normal faults.*
(*b*) *Reversed or overlap faults.*

In *normal faults* the *downthrow* of the beds or lode is towards the side to which the fault inclines or hades. Thus, in fig. 88 the hade and downthrow are both in the same direction. This is the most common type of fault; hence the name *normal.*

Here the seam of coal has been faulted down from *a* to *b* in the direction indicated by the arrow.

In reversed or overlap faults the downthrow of the beds is on the under or *foot-wall* side of the fracture, as shown in fig. 89.

In fig. 89 the hade is towards the west, but the downthrow is on the under or foot-wall side. That is, the seam has been displaced from *b* to *a*; or if we

assume that *a* is the original position of the seam, then it has been moved from *a* to *b*; that is, contrary to the direction of the hade.

In fig. 87 (*A*) we have an example of fracturing and faulting in the middle limb of overturned folds arising from the resistance of the granite boss to the lateral thrust from the right.

Displacements caused by Faults.—Faults cause different effects according to the direction of their strike and dip relatively to the strike and dip of the beds, seam, or lode they intersect.

A fault that runs parallel with the strike of the beds is termed a *strike-fault.* It may dip with the bed or against it.

A fault that runs in the same direction as the dip of the beds—that is, at right angles to their strike—is called a *dip-fault.* A fault, however, may pursue any course between the strike and dip of a bed; and in consequence the distinction between strike-faults and dip-faults is sometimes not very well marked. When the course of the fault is midway between the dip and strike of the bed, the fault may be termed either a dip-fault or a strike-fault.

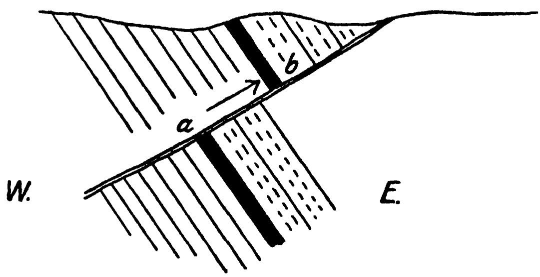


FIG. 89.—Cross-section showing reversed fault.

Faults according to their direction in respect of the beds or lodes they intersect may cause—

(1) A vertical displacement=*throw.*
(2) A horizontal displacement=*shift* of faulted bed.
(3) An *apparent* lateral displacement=*heave.*

The vertical displacement may vary from the fraction of an inch to thousands of feet. The great 10-yard seam of coal in Staffordshire has been thrown down 450 feet (fig. 101).

The horizontal shift of the dissevered portion of a bed may amount to thousands of feet, and is dependent on the amount of *throw* and the angle of inclination of the fault-plane, as will be shown later.

The apparent lateral displacement caused by faulting is dependent on the throw and the amount of denudation the country has suffered since the faulting took place.

When a fault displaces stratified rocks, the lines of bedding afford a measure of the vertical displacement; but, in the absence of some rock marked by a distinctive peculiarity of colour or composition, there is no means of estimating the amount of disturbance.

Effects of Faults on Horizontal Strata.—When a vertical fault intersects a horizontal bed, such as a seam of coal, the only displacement is a vertical one, but inclined faults cause both vertical and horizontal displacement.

In fig. 90 a horizontal seam of coal is intersected by faults *A*, *B*, and *C*; *A* being vertical, *B* steeply inclined, and *C* relatively flat.

It is obvious that the vertical displacement or *downthrow,* commonly

called *throw* by miners, equal to *m n*, is the only displacement caused by the vertical fault *A*. There is no horizontal displacement.

Fault *B* is inclined to the east, and causes a vertical displacement *d s*, and a horizontal displacement *d e*, which represents the horizontal disseverment of the ends *e* and *s*.

Fault *C* produces the same amount of downthrow as fault *B*, but being much flatter, it causes nearly four times as much horizontal displacement; that is,

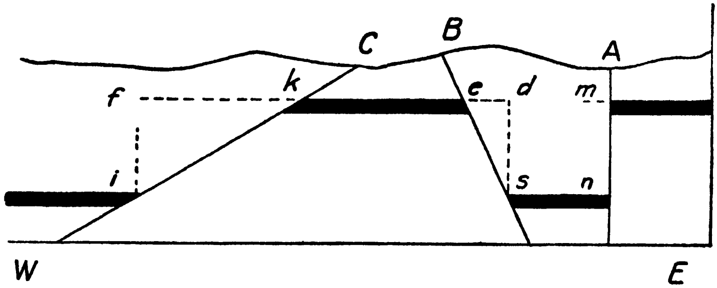


FIG. 90.—Showing effects of normal faults on a horizontal bed or seam.

$f\,k = 4\,e\,d$. It is obvious that the *flatter* the plane of the fault, the *greater* will be the horizontal displacement.

The expressions *downthrow* and *upthrow* as used by miners are merely co-relative terms applied to the vertical displacement. Thus, if the mine workings were advancing from *n* to *s*, the direction of the faulted seam *e k* would be spoken of as an *upthrow*. If, on the other hand, the direction of the workings was from *k* to *e*, then when the fault was encountered the position of the seam at *s n* would be said to be the result of a *downthrow*.

The faults *A*, *B*, *C*, shown in fig. 90, are examples of normal faulting.

Summarising the foregoing, we find that when an inclined fault intersects a horizontal bed or seam the displacements are

(*a*) A vertical downthrow (or upthrow) = *throw*.

(*b*) A horizontal disseverment due to the faulted portion sliding down the fault-plane. For the same *throw*, the flatter the fault-plane, the greater will be the horizontal shift.

Do not fail to note that no lateral displacement or *heave* has taken place in the examples of faulting shown in fig. 90, where we have only vertical downthrow with fault *A*, and downthrow and disseverment with faults *B* and *C*.

Effects of Strike-Faults.—A strike-fault runs parallel with the strike of

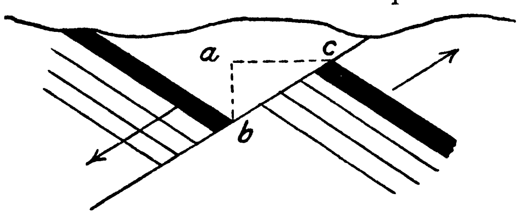


FIG. 91.—Showing effects of strike-fault dipping contrary to the dip of the strata.

the bed or seam. It may dip with the bed or against it, and according to the direction of the hade it may be a normal or reversed fault.

A strike-fault causes vertical and horizontal displacements of the beds intersected, as shown in fig. 91.

In this figure the vertical downthrow$=a\ b$, and the horizontal shift$=a\ c$.

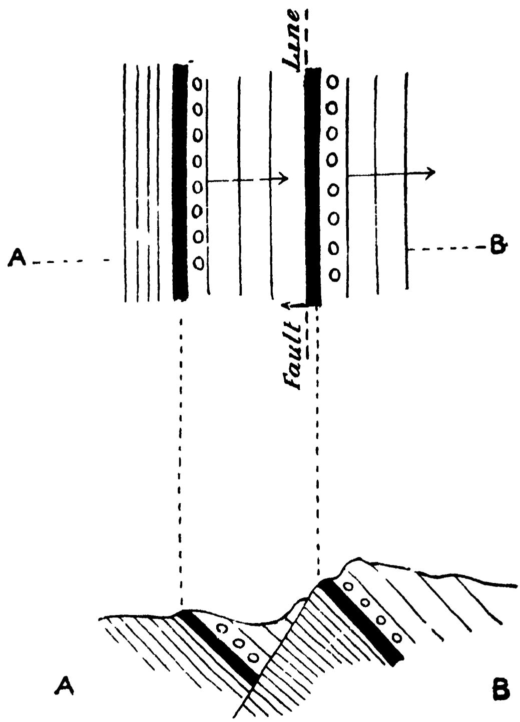


Fig. 92.—Showing repetition of inclined beds. Upper diagram is map of beds traversed by strike-fault. Lower diagram is a cross-section along line *A B*, showing repetition of dislocated beds.

A strike-fault causes a repetition of inclined beds, as shown in fig. 92. In regions that have suffered considerable denudation, a faulted bed or

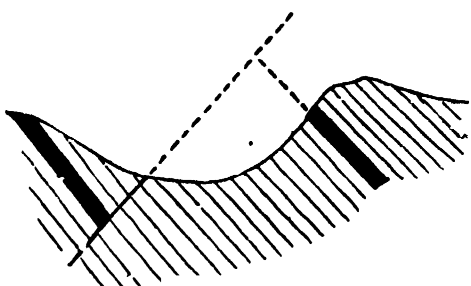


Fig. 93.—Showing coal-seam partly removed by denudation on one side along line of strike-fault.

seam of coal may be partly removed on one or both sides of the fault, as shown in fig. 93.

Thrust-Planes.—Strike-faults may dip or hade in the same direction as the beds they intersect, and the angle subtended between the bedding planes

and fault-plane may be so small that the plane of movement eventually follows the bedding as offering the line of least resistance.

When the dip and strike of the fault coincide with the dip and strike of the beds, there is no apparent disturbance in the relationship of the rocks on each side of the fault-fracture.

The only evidence of the existence of such a fault is the smooth, polished, and slickensided surfaces on the plane of movement.

In some cases the movement along a *thrust-plane* has crushed the wall-rocks into fragments, forming what is called a *friction-breccia*. The friction-breccia produced in this way may be a few inches or many feet wide. The fragments are usually held together in a matrix of clay or *pug* resulting from the attrition of the walls; and not infrequently many of the rock fragments are partially rounded and even sometimes scratched and striated by the grinding effect of the wall-movement.

Effect of Dip-Faults.—The course of *dip-faults* is more or less parallel with the dip of the beds or veins intersected.

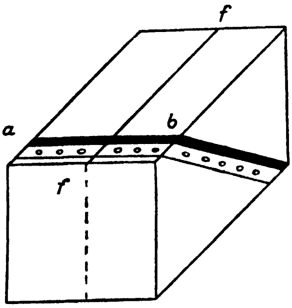


FIG. 94.—Showing dip-fault intersecting inclined coal-seam before faulting (represented by wooden model).

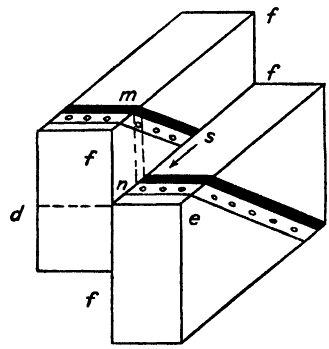


FIG. 95.—Showing displacement caused by dip-fault after faulting.

On the slickensided faces of great faults, the striæ caused by the rubbing of one rock-surface upon the other usually follow a vertical plane. In other words, there is no side shift of the faulted bed. Consequently, when the faulted beds are vertical, there is no lateral displacement or *heave*, as the dissevered ends merely slide upon one another in a vertical plane.

The apparent heave or lateral displacement is produced by the dip of the seam carrying the faulted portion of the seam to the right or left; and, manifestly, the flatter the dip, the greater will be the apparent displacement. When the seam or lobe is vertical, there can obviously be no heave; for since the movement is vertical, the fractured faces will merely slide on one another.

Let *a b* in fig. 94 represent an inclined coal-seam, and *f f* a fracture. When faulting takes place, the effect will be as shown in fig. 95.

Here *m n* represents the downthrow or vertical displacement; and it will be observed that there is no horizontal shift, since the fault-plane is vertical. Moreover, it will be observed that the outcrop *m* is vertical above the faulted outcrop *n*.

When the ground on the high side is worn down by denudation to the level of *d e*, there is displayed an apparent horizontal displacement of the dissevered

seam from *s* to *n*, fig. 96, and *s n*=the *heave*, which is not real but the result of the vertical movement followed by denudation. And clearly the portion of the seam exposed at *s* by denudation does not correspond with the portion cropping out at *n*.

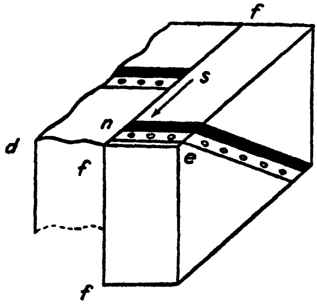


FIG. 96.—Showing apparent heave.

If the fault inclines to one side, as in fig. 97, then we shall have a vertical downthrow=*a b*, and a horizontal shift *b c*, which will represent the horizontal disseverment due to the faulted portion sliding on the sloping fault-plane. And, obviously, the flatter the dip of the fault, the greater will be the *shift* for a given *throw* or vertical displacement.

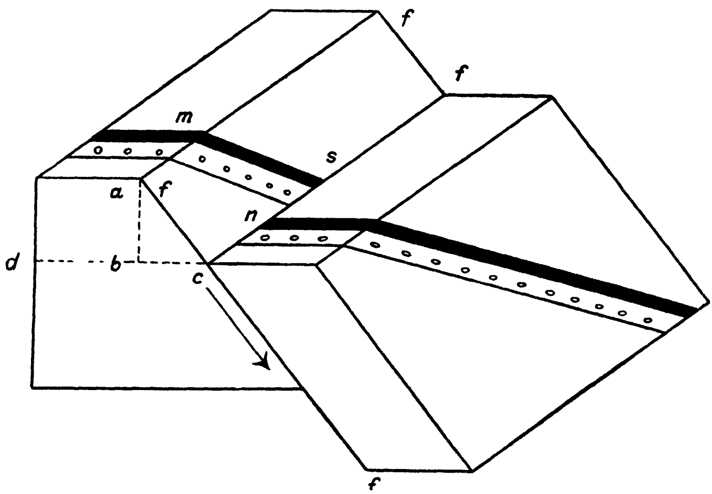


FIG. 97.—Showing effects of inclined dip-fault on tilted coal-seam.

If now we suppose that the elevated portion of the seam is denuded down to the level of *d c*, then there will be an *apparent heave*=*s n*; but, obviously, the portion of the seam at *n* will not correspond to the portion at *s*, but to the summit of the portion of *m*, now removed by denudation.

Furthermore, when the upthrow side is denuded down to the level of *d c*, the evidence of the *horizontal shift b c* will be removed.

Effect of Dip-Fault on Syncline.—When a block of strata arranged in the form of a syncline is traversed by a dip-fault and the ground on the high side is denuded down to the level of the low side, the lines of outcrop on the high

side will appear *inside* the lines on the low side, since they represent a narrower portion of the syncline, as shown in fig. 98.

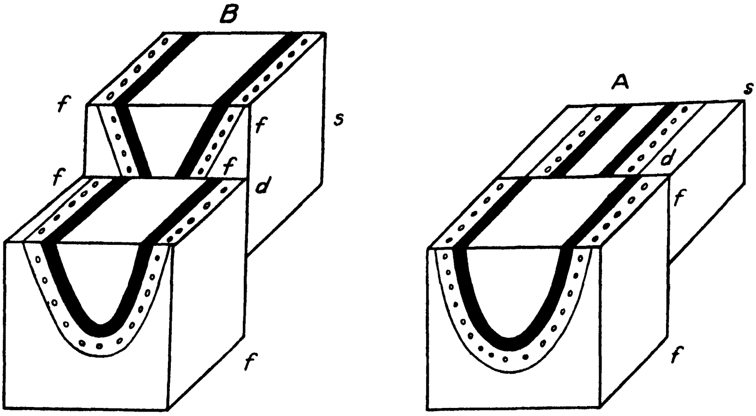


FIG. 98.—Showing effect of dip-fault on a syncline. Diagram *A* shows the appearance of the outcrops after faulting and denudation ; diagram *B*, after faulting, but before denudation.

Effect of Dip-Fault on Anticline.—The effect in this case is the opposite of that produced on a syncline ; that is, the outcrops of the denuded portion will

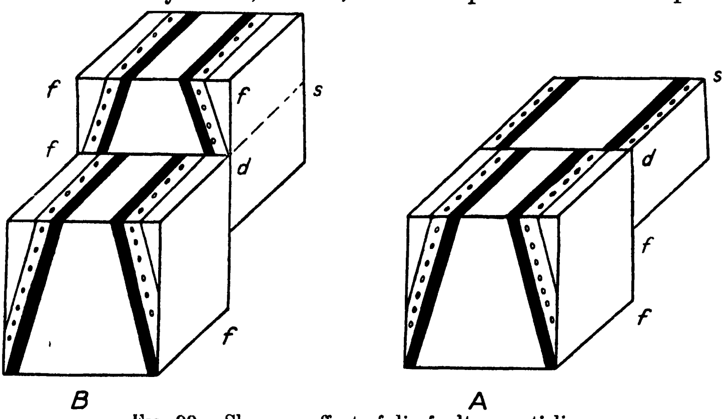


FIG. 99.—Showing effect of dip-fault on anticline.
A, After denudation. *B*, Before denudation.

appear *outside* the lines of outcrop on the downthrow side, as shown in *A*, fig. 99.

Step-Faults.— Extensive subsidence or elevation is usually accomplished

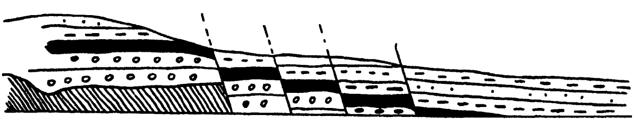


FIG. 100.—Showing effect of step-faulting.

by the production of a number of parallel faults. When the dip of the faults is in the same direction, there is frequently produced a succession of downthrows that in cross-section resemble the steps of a stair ; hence the name *step-fault* (fig. 100).

The displacement caused by step-faults is usually small, and is best seen when the faults dislocate a coal-seam.

Trough-Faults.—When two parallel fractures permit a block of strata to be thrown down between them, they form what is called a *trough-fault*. A well-known example is the trough-fault of Dudley Port Mine in Staffordshire, which has thrown down the great 10-yard seam of coal a vertical distance of 450 feet (fig. 101).

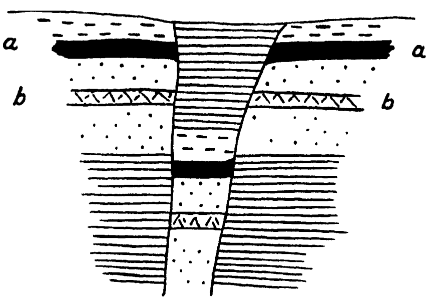


FIG. 101.—Showing effect of trough-fault.
(*a*) Seam of coal. (*b*) Sheet of basalt.

When the area depressed by trough-faulting is of considerable linear extent, it forms what German geologists call a *Graben*.[1]

Field Evidence of Faults. — Many faults, perhaps the majority, give rise to no surface feature by which we might be led to suspect their existence. The surface evidences of the dislocation caused by minor faults and those of great antiquity have been obliterated by the denudation the land has undergone since the faulting took place. Only powerful faults of late date modify the topographical features in such a way as to proclaim their presence.

The great Moanatairari Fault, which traverses the Thames Goldfield, and displaces all the gold-bearing lodes lying in its path, is of such recent date that its course may be traced on the surface for many miles, being marked by a distinct line of depression, as well as by the downthrow and displacement of the spurs which it crosses. It dips to the south-west at a uniform angle of 45°, and wherever it is cut in the mine workings its course is marked by a layer of friction-breccia and clay, varying from 20 to 100 feet thick. Its vertical displacement amounts to about 400 feet.

Faults are rarely visible at the surface except in bare cliffs and artificial cuttings. As a rule they are obscured with a sheet of younger detritus. Even the clean fault-fractures so frequently seen in cliffs and railway-cuttings may be mere local dislocations, or branches radiating from some greater fault.

The majority of the faults that traverse the coal-fields of Great Britain, North France, Belgium, Pennsylvania, New South Wales, and other countries, were unknown till their presence was disclosed by the progress of underground mining.

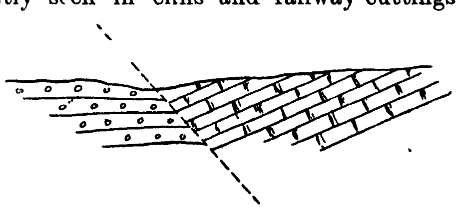


FIG. 102.—Showing existence of fault inferred from presence of abutting limestone and conglomerate.

When once the position, course, and dip of a fault are ascertained, its position in contiguous areas can be predicted with a certain degree of accuracy, provided no later faulting or dyke intrusion has diverted it from its normal course.

Since, then, the topographical effects and actual fractures of faults are seldom seen at the surface, the geologist is compelled to depend on the inference to be drawn from certain field occurrences as to the existence of faults. Thus, when two members of the same formation are found abutting against one another, as shown in fig. 102, it is inferred that a fault exists at the line of contact.

[1] Ger. *Graben*=ditch or trench.

Again, the repetition of a series of beds, or of some of the beds, in the absence of folding, is always held to be an evidence of faulting, as shown in fig. 103.

Where a younger series of strata occupying the floor of a valley or inland basin is tilted on end, may be for scores of miles against an older formation, as frequently happens along the foot of a mountain-chain, the evidence is held to indicate profound dislocation or faulting of an orogenic character. Such faulting has taken place in the Great Basin of the Western States of North America and in the inland basins of Otago in connection with the uplift of the *block* mountains in those regions (fig. 104).

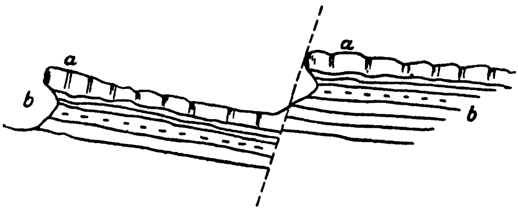


FIG. 103.—Showing existence of fault inferred from repetition of beds.

The existence of an unseen fault may be, as a rule, determined by the detailed examination and mapping of a district. By its effect on the geological structure, the position and course of the fault, as well as its vertical displacement, can be worked out without the actual fracture being seen in a single section on the surface.

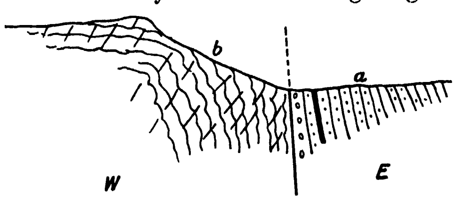


FIG. 104.—Showing faulting of young Tertiaries against mica-schist in New Zealand.

(*a*) Young Tertiary lacustrine beds.
(*b*) Palæozoic mica-schist.

In coal areas and goldfields, the faults proved to exist by the underground workings always afford a valuable aid to the field-geologist.

Many valleys have been excavated along the course of faults; hence persistent escarpments on the valley-walls are always suggestive of faulting.

Lines of springs frequently follow the course of faults, and should be carefully noted. The sheet of stiff clay which lies along the walls of fault-fissures arrests the flow of underground water which eventually finds its way to the surface in the form of springs. The existence of a mineral vein may also be indicated by a line of springs.

Cleavage.

Cleavage Structure.—Shales and other rocks composed of fine sediments possess a tendency to split into laminæ parallel to the original bedding planes, and this is the natural thing to expect from the manner in which the sediments were laid down. Many of the older fine-grained rocks, however, possess a tendency to split into plates or thin flags at *right angles* to the original stratification planes. This peculiar structure is best exemplified in roofing slates, and is called *cleavage* or, more correctly, *slaty cleavage*, to distinguish it from the natural cleavage possessed by many crystalline minerals.

Although cleavage is, as a rule, best developed when at right angles to the bedding planes, it may intersect these at any angle, or may even be parallel with them. The slates at Collingwood[1] possess a distinct cleavage that in

[1] "The Geology of Collingwood County, N.Z.," *Geol. Surv. Repts.*, 1888–89, p. 210 (1890).

different places intersects the stratification planes at various angles from 30° to 45°.

When examined under the microscope, in thin slices, the constituent particles of a slate are found to be elongated in a direction parallel with the cleavage-planes. It is this parallelism of the grains that enables a slate to split readily into thin plates.

Where the cleavage is well developed, the original stratification planes become obscure, or they may be altogether obliterated. In highly altered slates, crystalline minerals, such as mica and rutile (the former most abundantly) are frequently developed along the cleavage-planes. In this way we are able to trace the alteration of shale to slate, of slate to phyllite or mica-slate, of phyllite to mica-schist, and of mica-schist to gneiss.

Origin of Cleavage.—Cleavage is the result of enormous lateral pressure. The cleavage-plane is always perpendicular to the line of pressure. It is usually best developed where the rocks have been subjected to intense folding combined with sufficient superincumbent weight to prevent the loss of lateral stress by the upward yielding of the strata. Near the surface the rocks will yield and fracture before the lateral pressure becomes sufficient to cause the component particles to be elongated or rearranged at right angles to the compressing force. Hence it is found that slaty cleavage is always best developed in ancient sediments that have been subjected to prolonged compression in deep crustal folds.

Sandstones, conglomerates, and altered igneous rocks frequently exhibit an incipient form of cleavage that is, however, usually short and irregular.

Slaty cleavage is not confined to rocks of any particular age, but is seldom met with in formations younger than the Jurassic. The fine roofing slates of Wales, of Cambrian age, are remarkably fissile and homogeneous in texture.

Cleavage, in all respects similar to that induced in slates, has been imitated by mechanical means in various mixtures of clay by Sorby and other experimenters.

Slates that have been subjected to a torsion or twisting stress through the obstruction offered by an unyielding buttress of rocks lying in the path of the compressive force are found to break up readily into thin prismatic pencils.

SUMMARY.

Joint-Structure.—(1) The majority of sedimentary rocks, both altered and unaltered, are traversed by two sets of simple cracks called *joints*, that are usually perpendicular to the original bedding planes and at right angles to one another, thereby dividing the rock-mass into cuboidal or prismatic blocks.

Joints are commonly confined to the particular rock in which they occur, but in some cases they are found to pass from one rock to another. The best-developed joints are known to workmen as *master-joints*.

Some igneous rocks are traversed by two sets of joints that divide the rock-mass into symmetrical columns, giving rise to the well-known *columnar structure* which is particularly well developed in some basalts.

Joints are necessarily confined to the zone of fracture, and in the majority of cases they are not continuous but die out when followed in any given direction, being succeeded after an interval by others having the same general course.

Joint-planes sometimes show polished and striated faces which indicate rubbing or attrition due to some movement.

The joints that are so frequently found traversing seams of the older coals are termed *cleats*. The *face cleats* run parallel with the strike and are usually

the most pronounced. The *butt cleats* are perpendicular to the face cleats. The master-joints in rocks and the cleats in coals are utilised by the workmen to facilitate the breaking of the material.

Origin of Joints.—(2) Joints are in all probability caused by tension stresses arising from folding and earth-movements resulting from shrinkage and shearing. The master-joints usually run parallel with the axis of elevation, which points to a genetic relationship between joints and folding.

In anticlinal folds, the upper layers of rock will be in tension and the lower in compression ; while in a syncline, the lower layers will be in tension and the upper in compression.

Faults.—(3) A fault is a simple crack or fissure on one side of which movement has taken place so as to shift the rocks on each side relatively to one another.

Faults are caused by crustal stresses of greater magnitude than those that originated jointage. Joints and faults are closely related, and both are the visible expression of mechanical stresses. Sharp folding results in fracturing and faulting whenever the stress exceeds the elastic limit of the rock-mass.

Faults begin gradually, somewhere along their course attain a maximum displacement, and then gradually die out. Or faults may be cut by other faults, so that they end suddenly. Their length may vary from a few hundred feet to hundreds of miles, and their vertical displacement from a fraction of an inch to many thousand feet.

The faces of fault-planes are frequently polished, grooved, and striated—that is, *slickensided.* In many cases, perhaps the majority, the fault-fissure is filled with a sheet of clay resulting from the attrition of the rock-surfaces. In other cases they are filled with fragments of rock. In many cases fault-fissures have formed channels for the circulation of underground waters which have deposited mineral matter and metallic ores in them. Many faults have in this way become changed into valuable lodes.

(4) In what is called a *normal* fault the downthrow is towards the side to which the fault inclines ; and in a *reversed* or *overlap* fault the downthrow is on the footwall side, or the movement has brought the hanging block in a position above the other.

(5) A fault, according to the direction it pursues in relation to the strike of the rocks it traverses, may be a *strike-fault* which runs parallel with the strike, or a *dip-fault* which runs at right angles to the strike. But it must be remembered that faults may run at any angle between the strike and dip.

A strike-fault causes both vertical and horizontal displacement of the beds it intersects, and if the *throw* is considerable, may cause a repetition of the surface outcrops of a succession of beds.

(6) Dip-faults cause a vertical and an apparent lateral displacement, the last due to the dip of the faulted beds carrying the faulted portion to the right or left.

Where parallel faults cause a displacement in the same direction, they form what are called *step-faults* ; and where two faults dip towards each other so as to permit a block of rock to drop down between them, they form a *trough-fault.*

(7) Among the best field-evidences of faulting are (*a*) the side displacement of beds, and (*b*) the repetition of beds where there is no reason to suspect the existence of isoclinal folding. Few faults are recognisable on the surface, as in the majority of cases denudation has kept pace with the rate of displacement. Their existence can, however, be deduced from the deposition and arrangement of the rocks, as shown by a careful geological survey. Faults are easily

recognised in coal and metal mines by the displacement of the seams and lodes which they intersect.

Cleavage.—(8) This is the tendency possessed by many rocks, particularly those of fine texture, to split into thin plates in some direction not parallel to the original bedding plane. Cleavage is best seen in clay slates. It can be induced in artificial mixtures of clays, iron oxide, etc., by the application of enormous lateral pressure. The cleavage-plane is always perpendicular to the line of pressure. It is believed that slaty cleavage is the result of lateral pressure or compression arising from crustal folding.

CHAPTER XII.

COMPOSITION OF EARTH'S CRUST.

Constitution and Physical Properties of Minerals.

THE crust of the Earth is composed of rocks and minerals that, in their ultimate constitution, consist of elementary substances called elements.

Some Chemical Principles.—*Elements* are simple substances, and of these, chemical research has identified about seventy in the various rocks, minerals, and compounds that constitute the accessible portion of the crust. The majority are, however, comparatively rare.

Elements and their compounds exist naturally in three conditions, namely, gaseous, liquid, and solid.

Most solids can be rendered liquid by the application of heat; and by applying still more heat, the liquid form can be changed to the gaseous. Conversely, by the application of sufficient cold and pressure, the gases can be made first liquid and then solid.

Of the metallic minerals, mercury is the only one that is liquid at ordinary temperatures. It can be converted into a solid by subjecting it to the influence of intense cold.

The majority of the elements do not exist in a *free* or *uncombined* state, but two, three, or more combine with one another to form various compounds. A compound may be a gas, like carbon dioxide; a liquid, like water; or a solid, like calcite or limestone.

Among the elements that exist in a free state we have the gases oxygen, nitrogen, and chlorine; the liquid, mercury; and the solids, gold, silver, platinum, copper, iron, carbon, sulphur, and some others.

Practically, all the elements resent an existence in a free state, and hence are always on the alert to form alliances with other elements or compounds.

The chemical affinities or likings of some elements for certain other elements are very powerful and for others feeble. The gas *fluorine*, for example, is so active that it can only be separated from its compounds with the greatest difficulty, and when separated it requires the exercise of extraordinary precautions to keep it from combining with other elements. On the other hand, *nitrogen*, when free, is not very active, and it is for this reason that it constitutes so large a proportion of the atmosphere.

An element may possess the power to combine with many different elements with various degrees of intensity. With those to which it is strongly attracted, it will form stable compounds, and with those to which it is feebly attached, feeble combinations that are easily broken up.

Thus *silicon* has a powerful attraction for oxygen, and when once these two elements are united, as we find them in *silica* (SiO_2), which occupies such an important place among the constituents of the Earth's crust, it is almost

impossible to dissociate them. On the other hand, iron and oxygen have a mutual attraction, forming *oxides of iron*, but the oxygen can easily be displaced from the iron by presenting carbon to it under suitable conditions. In fact, the oxides of almost all the metals can be broken up by carbon, and this is the principle that underlies the reduction or smelting of the base metals.

What has been said of the elements is also true of many compounds, particularly of the gaseous compounds and the salts soluble in water. That is, they possess the power to unite with elements or other compounds to form new compounds. They also, like the elements, possess certain affinities, preferring to unite with certain elements and compounds in preference to others. Likewise with certain elements and compounds they are capable of forming stable combinations, while with others they form feeble combinations. Thus the union of lime (CaO) and carbonic acid (CO_2) is a comparatively stable compound forming calcite, limestone, or chalk; but the soluble bicarbonate of lime, which is formed when carbonic acid dissolved in water acts on limestone ($CaCO_3$), is a feeble combination, the excess of carbon dioxide being easily displaced.

The inveterate natural propensity and continual struggle of certain elements and compounds to form new and attractive combinations more to their liking, is the dominant principle underlying the weathering and disintegration of rocks which play so important a *rôle* in the general processes of denudation.

The three compounds responsible for the greater part of this disturbance are silica (chemically called *silicic acid*), *carbonic acid*, and *sulphuric acid*. Next to these we have the elements oxygen and chlorine, both active and powerful allies of the acids.

The acids unite with the oxides of the metals called bases to form new compounds. Thus—

Silicic acid, *i.e.* silica, forms *silicates*.
Carbonic acid, *i.e.* carbon dioxide, forms *carbonates*.
Sulphuric acid forms *sulphates*.
Oxygen unites with metals to form oxides, or unites with lower oxides to form higher oxides.
Chlorine unites with metals to form chlorides.

The silicates, carbonates, and sulphates are important in any study of the crust on account of the dominant part they play as rock-forming minerals.

Of the eighty or more elements distinguished by chemical science, about twelve constitute about 97 per cent. of the mass of the accessible crust. These twelve are as follows:—

Element.	Percentage in Crust.
Oxygen,	47
Silicon,	28
Aluminium,	8
Iron,	6
Calcium,	4
Magnesium,	2
Sodium,	2
Potassium,	2
Carbon, chlorine, barium, and manganese,	about 2

Some Physical Properties of Minerals.

A Mineral Defined.—The term *mineral* embraces such a wide range of natural substances that it is difficult to formulate a definition sufficiently comprehensive and exact to satisfy scientific requirements. A mineral may, however, be defined as *a natural, homogeneous, inorganic substance possessing a definite chemical composition.*

This definition includes *water* and its solid form *ice*, but excludes coal and some other substances of vegetable origin that are by common usage regarded as minerals.

The most important physical properties of minerals are the following:—

1. Crystalline form.	5. Tenacity.
2. Cleavage.	6. Specific gravity.
3. Fracture.	7. Lustre and feel.
4. Hardness.	8. Colour and streak.

Formation of Crystals.—Crystals may be formed in Nature in three different ways, namely:—

(1) By sublimation from gases.
(2) By chemical precipitation from solutions.
(3) By separation from a fused or molten mass.

In volcanic regions the sides of the vents of *fumaroles* and of all the cavities or vughs to which the gases have access, are frequently lined with beautiful incrustations of sulphur crystals formed by sublimation through the mutual interaction of sulphuretted hydrogen and sulphurous acid gases emanating from the ground.

The formation of crystals by precipitation from aqueous solutions is a subject of which we have many familiar examples. If a hot saturated solution of brine be allowed to cool, crystals of rock-salt will separate out from the mother liquor. Or when a string is suspended in a saturated cooling solution of sugar, it soon becomes covered with the beautiful crystals called rock-sugar or barley-sugar. The crystalline *gangue* or matrix of mineral lodes is now believed to have been formed by precipitation from mineralised waters that at one time circulated in the fissures.

Crystalline Form.

All minerals have a tendency to occur in certain definite geometrical forms which are called *crystals*. There are hundreds of crystal forms, but all can be referred to six groups to which the name *crystallographic systems* is applied. They are as follows:—

1. Cubic or Isometric.	4. Monoclinic.
2. Dimetric or Tetragonal.	5. Triclinic.
3. Trimetric or Orthorhombic.	6. Hexagonal.

In every crystal the flat surfaces or faces are called *planes*, and these may be flat, rough, or curved. The line formed by the meeting of two planes is an *edge*, and the point where three or more planes meet is called a *solid angle.*

All crystals may therefore be regarded as solid geometrical figures bounded by *planes* or *faces*; and although the size of the planes may vary, as they do in large and small crystals, the angles between corresponding planes in different crystals of the same mineral are always the same.

In all crystals the planes are referred to certain imaginary lines called *axes*

running through the crystal. This construction is easily understood by the examination of wooden or glass models, but can also be made clear by a few simple experiments, now to be described.

Cubic or Isometric[1] System.—Take a piece of soap, transparent if procurable, and cut it into a cube about two inches square. Through the centre of each pair of opposite planes push a fine knitting-needle, as shown in fig. 105.

It will be observed that the three needles or axes lie at right angles to one another, and that the distance from the *centre* or point of intersection inside the crystal to each plane is the same.

Thus, in the cubic system we have three axes of equal length and at right angles to one another; and all the axes being equal, there is no axis that can be regarded as the principal axis in preference to the others.

If now we truncate the solid angles of the cube down to the points where the needles emerge, we shall get an eight-sided figure or *octahedron*.

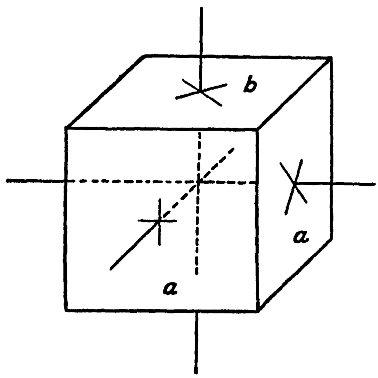


FIG. 105.—Showing cube with its three axes at right angles to one another.
(*a–b*) Pinacoid faces.

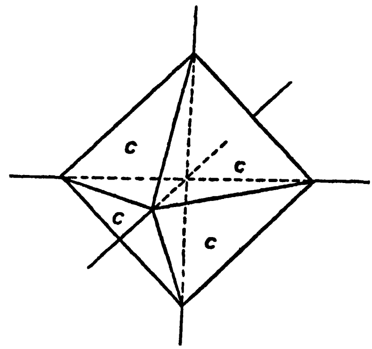


FIG. 106.—Showing octahedron.
(*c, c*) Pyramid faces.

By truncating various solid angles and edges we may obtain many modifications of the cube, all of which can be referred to the three axes of the cubic system.

Dimetric[2] or Tetragonal[3] System.—Take another piece of soap and cut it into a prism three inches long, with ends an inch and a quarter square. Mark the centre of each face, and through the marks in each pair of opposite faces push a needle (fig. 107, *A*).

Here we have three axes, all at right angles; two are of equal length and lie in the same plane, while the third is either longer or shorter than the others and is called the *principal* axis. In our example shown in the last figure we have made it longer than the others.

Observe that the *pinacoid*[4] faces or planes *a, a* are *parallel* to the principal axis, and *perpendicular* to the *lateral* axes.

The top and bottom planes of the prism are marked *b, b*, and are crystallographically called *basal* planes, notwithstanding their position at the top and bottom of the prism.

[1] Gr. *isos*=equal, and *metron*=a measure.
[2] Gr. *dis*=double, and *metron.*
[3] Gr. *tetra*=four, and *gonia*=an angle.
[4] Gr. *pinax*=a plank, and *eidos*=like.

If now we truncate or pare away the vertical edges of the prism until the new planes meet at the points where the lateral axes emerge, as in *B* of fig. 107, we shall obtain a new prism, bounded at the ends by *basal* planes, *b*, *b*, and at the sides with four new vertical planes lying *parallel* with the principal axis and *touching* two of the *lateral* axes. These planes are marked *p*, *p* (*prisms*), to distinguish them from the *pinacoids*, each of which, as we have seen above, is *perpendicular* to a lateral axis.

If we take another prism similar to the first used to illustrate this system, as shown in *A* of fig. 107, and truncate the eight solid angles, we shall obtain an octahedron bounded with pyramid faces *c*, *c*.

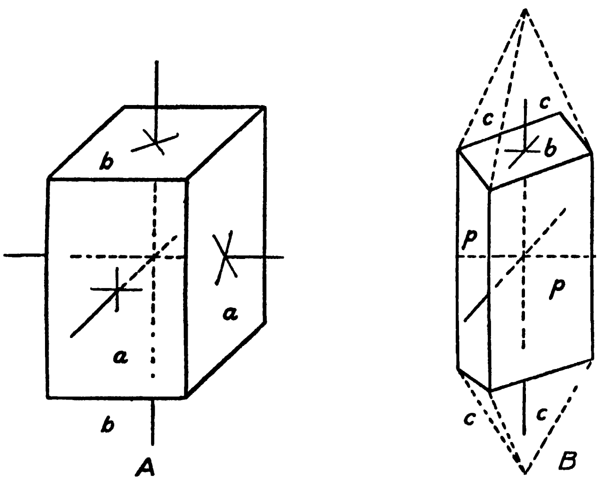


FIG. 107.—Showing prisms of dimetric system.

(*a*, *a*) Pinacoid faces.
(*b*, *b*) Basal planes.
(*p*, *p*) Prism faces.
(*c*, *c*) Pyramid faces.

Trimetric [1] or Orthorhombic System.—Cut a prism with oblong ends, and, as before, insert the needles through the centres of the opposite faces (fig. 108).

It will be seen that the three axes are still at right angles to one another, but that all are of different length. Here also the principal axis may be longer or shorter than either of the lateral axes.

By truncating the solid angles we obtain an octahedron bounded by pyramid faces; and by truncating the vertical edges of another prism similar to the one we started with, as shown in fig. 108, we obtain a prism bounded by prism faces.

Monoclinic [2] or Oblique System.—In this system there are three unequal axes, two at right angles, the third inclined.

To illustrate this system, first cut a prism three inches long, with ends, say, one inch by an inch and a half. Insert a needle through the centre of the top and bottom, *i.e.* basal planes, and another through the centre of the pinacoid planes lying parallel with the longer axis. These two needles or axes will be at right angles, but are of different lengths.

Now pare away the basal planes so that the model will not lie vertical when placed on the table. Make both basal planes parallel to one another,

[1] Gr. *treis*=three, and *metron*=a measure.
[2] Gr. *monos*=single, and *klino*=I bend or incline.

and through their centres push the third needle. The third axis will be seen to be inclined to the other two (fig. 109).

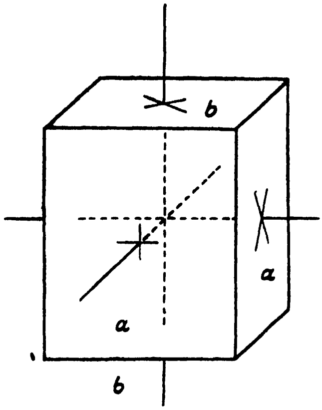


FIG. 108.—Showing prism of trimetric system.
(*a*, *a*) Pinacoids.
(*b*, *b*) Basal planes.

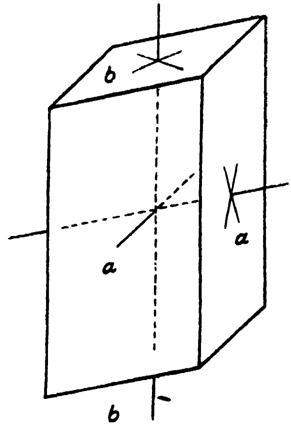


FIG. 109.—Showing prism of monoclinic system.
(*a*, *a*) Pinacoids.
(*b*, *b*) Basal planes.

Triclinic [1] or doubly Oblique System (fig. 110).—In this system there are three unequal axes, and all inclined at different angles.

Take the prism of soap used in the last experiment and pare the basal planes

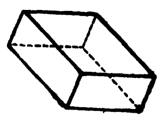


FIG. 110.—Doubly oblique prism of copper sulphate.

away in a direction at right angles to the first paring which caused the inclination of the prism. The prism will now be inclined in two directions.

Hexagonal System.—This system differs from all the others in having *four*

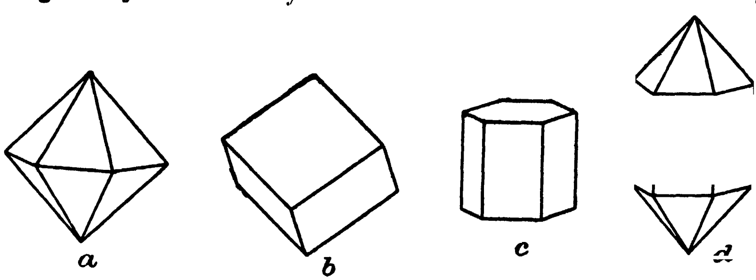


FIG. 111.—Hexagonal crystals.
(*a*) Hexagonal dodecahedron. (*b*) Rhombohedron. (*c*) Hexagonal prism.
(*d*) Crystal of quartz (combination of hexagonal prism and pyramid).

axes, of which three are equal, lie in the same plane, and are inclined to one another at an angle of 60°. The fourth, called the principal axis, is at right angles to the others, and may be of any length.

[1] Gr. *treis*=three, and *klino*=I bend or incline.

Cut a hexagonal prism three inches long, and through the centres of the opposite pairs of faces insert the needles. By truncating the solid angles a hexagonal pyramid will be obtained.

Recapitulation of Crystallographic Systems.

(1) Cubic—3 axes, all equal, all at right angles.
(2) Dimetric—3 axes, two equal, all at right angles.
(3) Trimetric—3 axes, all unequal, all at right angles.
(4) Monoclinic—3 axes, all unequal, two at right angles, the other inclined.
(5) Triclinic—3 axes, all unequal, all inclined.
(6) Hexagonal—4 axes, three equal, lying in the same plane, the fourth at right angles to others.

In all the systems there may be prisms and pyramids. When crystals are very narrow and long, they are termed *acicular* or needle-shaped; and when broad, they are said to be *tabular*.

Pseudomorphs.[1]—These are crystals which have the form of one mineral and the composition of another. For example, crystals of quartz are frequently found in the form of calcite, and orthoclase is sometimes partly or entirely replaced with *cassiterite*, tin oxide.

Fossil organisms are frequently found replaced with *pyrites* or silica.

Pseudomorphism is the result of mineral *replacement*.

Dimorphism.[2]—A mineral substance that is capable of crystallising in two different systems is said to be *dimorphous*. Carbonate of lime is a notable example of dimorphism. In the form of *calcite* it crystallises in the hexagonal system, and as *aragonite* in the trimetric system.

Macles or Twin Crystals.—These are groups of two or more crystals that appear as if mutually intersecting one another, and sometimes as if a crystal had been cut in two and one part turned round on the other.

Macles are common in alum, albite, spinel, quartz, orthoclase, magnetite, pyrites, rutile, and many other minerals.

Geodes.—These are concretion-like masses, hollow and lined with crystals pointing inwards. They are common in all kinds of rocks and in mineral veins. The cavities which they filled are called *vughs*.

Measurement of Angles of Crystals.—The angles which similar planes make with one another are constant; and since minerals always crystallise in the same forms, the measurement of the angles affords an important aid in their identification.

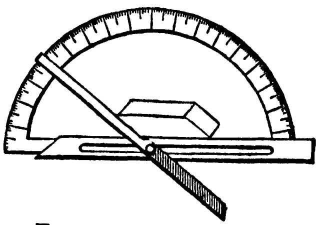


Fig. 113.—Showing simple goniometer.

The angles of crystals are measured with a goniometer,[3] of which there are many mechanical and optical forms. A simple form of goniometer is shown in fig. 113.

Cleavage. — This is the tendency possessed by many crystalline minerals to split or cleave in a certain direction. The cleavages are usually parallel with the faces of one of the simple forms of the mineral. They are spoken of as *perfect* when smooth and easily obtained, and *imperfect* when rough or obtained with difficulty.

[1] Gr. *pseudos*=false, and *morphe*=shape.
[2] Gr. *dis*=double, and *morphe*.
[3] Gr. *gone*=an angle, and *metron*=a measure.

FIG. 112.—Showing geode of calcite. (After Bassler.)

Many minerals possess no cleavage-planes; while others may cleave in one, two, or more directions. When a mineral possesses two or more cleavage-planes, one cleavage is generally more easily obtained than the others.

Cleavage is always in the same direction in the same mineral; hence it is of great use in the identification of crystallised minerals.

Quartz possesses no cleavage; *mica* has one perfect cleavage parallel with the basal plane; and *orthoclase* has two cleavages, viz. parallel with the basal plane, and with one pinacoid. *Calcite* has a perfect cleavage parallel to all the faces of the rhombohedron; hence, if a large crystal of that mineral be broken, it will fall into a number of small rhombohedrons, each of which may be broken into still smaller crystals of the same form.

Crystal-cleavage is a character in some way connected with the molecular structure and building up of the crystal. It has no relationship to the slaty cleavage of rock-masses, which, as we have found, is a structure induced by enormous lateral pressure.

Fracture.—This relates to any broken surface other than a cleavage-plane. According to its form it may be—

(*a*) *Conchoidal* or shell-like, as in flint.
(*b*) *Even* or free from roughness.
(*c*) *Uneven* or rough, as in cassiterite.
(*d*) *Splintery*, as in serpentine and nephrite.
(*e*) *Hackly* or *wiry*, as in native copper.

Hardness.—This is a character of great importance in determinative mineralogy. It varies greatly in different minerals and slightly according to the face taken, and is generally expressed in terms of Mohs's scale, which ranges from 1 to 10.

Mohs's Scale of Hardness.

(1) *Talc*, easily scratched with finger-nail.	(6) *Felspar*, difficult to scratch with knife.
(2) *Gypsum*, difficult to scratch with finger-nail.	(7) *Quartz*,
(3) *Calcite*, easily scratched with knife.	(8) *Topaz*,
(4) *Fluor Spar*,	(9) *Corundun*
(5) *Apatite*,	(10) *Diamond*,

(4) and (5): not easily scratched with knife. (7) to (10): not scratched with knife.

Quartz is harder than steel; therefore it is not scratched with a knife.

A mineral is tested for hardness by finding a test-mineral which will just scratch it, and one below which will not scratch it. Its hardness lies between these.

Tenacity.—Minerals may be—

(*a*) *Tough*, like nephrite or jade.
(*b*) *Brittle*, like tourmaline.
(*c*) *Pulverulent*, easily reduced to powder.
(*d*) *Sectile*, may be cut with a knife, like kerate.
(*e*) *Malleable*, may be flattened by hammering, like native copper.
(*f*) *Elastic*, like mica, which may be bent, but regains its original form when pressure is removed.
(*g*) *Flexible*, like asbestos, which may be bent, but is not elastic.

Specific Gravity=S.G.—This is the weight of a mineral compared with the weight of an equal bulk of water. The specific gravity of water is taken as 1, or unity. The specific gravity of quartz is 2·6, which means that a cubic foot of quartz, or any given volume, weighs 2·6 times heavier than the same volume of water.

A cubic foot of water weighs nearly 62·5 lbs.; therefore a cubic foot of quartz$=2{\cdot}6\times 62{\cdot}5=162{\cdot}5$ lbs.

Specific gravity is a character that is frequently of great use in distinguishing minerals.

To determine S.G. of a Mineral Substance heavier than Water:—First method—

(1) Weigh the substance carefully in a pair of scales. Call this the weight in air$=a$.

(2) Suspend the mineral from one of the pans by a silk thread, and weigh

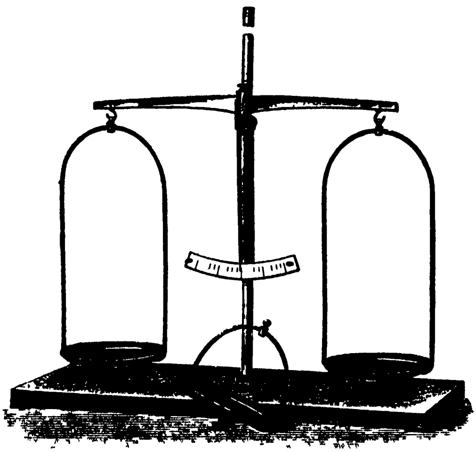


FIG. 114.—Showing specific gravity balance.

it in a vessel nearly full of water. Be careful to displace any air bubbles that may adhere to the surface of the mineral. Call this the weight in water$=b$.

(3) The weight in water will be less than the weight in air; that is, b will be less than a.

Subtract b from a, and the difference will be the weight of water displaced by the mineral.

(4) Divide the weight in air by the difference just found, and the quotient will be the S.G. required.

This may be expressed in the form of a simple equation—

$$\text{S.G.}=\frac{a}{a-b}.$$

Second method—

A more exact determination is made by means of a *specific gravity bottle,* which is a light glass bottle provided with a perforated stopper, arranged to hold, when full, a known quantity of water, say 500 grains.

(1) Fill the bottle with water, insert stopper, and wipe dry.
(2) Make a counterweight of lead-foil exactly equal to the weight of the full bottle.
(3) Reduce a portion of the mineral to be tested to a coarse sand. Remove all the fine dust, and weigh out a portion of the sand less than the capacity of the bottle, say 200 grains. Call this weight *a*.
(4) Put the weighed sand into the bottle, taking care to lose none. Some water will be displaced in doing so. The water so displaced will obviously equal the bulk of the sand introduced into the bottle.
(5) Again insert the stopper, wipe dry, and weigh, using the counterweight. It will be found that the counterweight *plus* a less weight than *a* will produce equilibrium. Call this weight *b*. Then as before—

$$\text{S.G.} = \frac{a}{a-b}.$$

Lustre and Feel.—Many minerals possess a characteristic lustre, which may be—

(*a*) *Metallic*, like galena.
(*b*) *Brassy*, like pyrites.
(*c*) *Resinous*, like blende.
(*d*) *Vitreous* or *glassy*, like calcite.
(*e*) *Silky*, like satin-spar and many fibrous minerals.

All the hydrous silicates of magnesia, as, for example, *talc* and *steatite*, feel *greasy* to the touch.

Actinolite and some other minerals feel *harsh*.

Colour and Streak.—The characteristic colour of many minerals is a valuable aid in their identification, especially in the case of those possessing a metallic lustre. The colour of earthy minerals is liable to great variation owing to the presence of impurities.

The *green* colour of *chlorite*,[1] *malachite*, and *glauconite*; the *blue* of *azurite*; the *scarlet-red* of *cinnabar*—are nearly always distinctive.

The *streak* refers to the colour of the powder of a mineral, and is best obtained by drawing the substance to be tested across a plate of unglazed porcelain.

The streak of metallic minerals is generally as dark, or darker, than the colour of the mineral; and of non-metallic minerals, as light, or lighter, than the colour.

Classification of Minerals.—The two systems of classification in common use are called the *Chemical* and *Economic*. In the *Chemical* classification the minerals are arranged according to their chemical composition; thus the carbonates, sulphides, oxides, and silicates are brought together into distinct groups, which are further subdivided into *hydrous* [2] and *anhydrous*.[3]

In the *Economic* classification all the ores and compounds of each metal are brought together in one group; thus, in the iron group we have metallic iron, and all the oxides, sulphides, etc., of that metal. This arrangement possesses many advantages from a commercial and technological standpoint.

[1] Gr. *chloros*=green. [2] Gr. *hydor*=water.
[3] Gr. *a*=without, and *hydor*=water.

CHAPTER XIII.

ROCK-FORMING MINERALS.

An Account of the more Common Minerals composing the Crust of the Earth.

ABOUT three-quarters of the surface of the globe are occupied by the sea, and one-quarter by dry land. The dry land is mainly composed of such massive rocks as sandstones, shales, slates, limestone, granite, various lavas, etc., but in geology, clay, sand, gravel, and other unconsolidated rocky materials are also classed under the general term *rock*.

Rocks defined.—Many rocks are aggregates of several distinct minerals, a good example being granite, which is composed of quartz, felspar, and mica. Some rock-masses are composed of some one mineral alone in a more or less impure state ; thus marble is an impure form of calcite, and dunite an impure massive form of olivine.

Examination of Rocks.—That branch of geology which deals with the study of rock-masses as seen in the field, and with the minute structure of rocks as determined in the laboratory, is called *Petrology*.[1]

The *megascopic* [2] examination of a rock refers to the results obtained by viewing the rock with the naked eye. The *microscopic* [3] examination refers to the study of the minute structure as seen in thin slices placed under the microscope.

Minerals occur in Two Conditions.—A mineral may occur in Nature in two conditions or forms, namely—

(1) *Crystalline*—that is, in more or less well-defined crystals.
(2) *Amorphous*—that is, massive, or without definite crystalline structure or form.

In mineralogy the crystalline form of a mineral is frequently given a distinct name ; thus the *diamond* is the name applied to the crystalline form of *carbon*, *corundum* of *alumina*, and *selenite* of *gypsum*.

A mineral may be chemically composed of—

One element, as the diamond, which is pure carbon.

Two elements, as ordinary table salt, composed of the metal *sodium* and the gas *chlorine*.

Three elements, as *calcite*, the principal constituent of all crystalline limestones, composed of the metal *calcium*, *carbon*, and *oxygen*.

Four or *more* elements, as the *garnet* and *mica*, which are complex and variable silicates of many bases.

[1] Gr. *petra*=a rock, and *logos*=description.
[2] Gr. *megas*=large, and *skopein*=to view.
[3] Gr. *micros*=small, and *skopein*=to view

Gold, silver, platinum, iron, lead, and mercury, and all the metals that occur in Nature in the *native* or metallic condition, are minerals. The chemical combinations of the metals with oxygen, sulphur, arsenic, fluorine, etc., are commonly spoken of as *ores*. For example—

Zinc+sulphur=ZnS=zinc blende.
Lead+sulphur=PbS=galena.

All the ores of the metals are classed as minerals, and their study forms an important branch of mineralogy.

Thus we find that oxygen, sulphur, etc., possess the property of combining with metals, or *bases* as they are then called, to form a group of minerals known as *ores*. Ores commonly occur aggregated in lodes or veins and in irregular deposits. As rock-forming minerals they are not important, with the exception of the compounds of iron, which are abundant and widespread.

Silicates and Carbonates.—Oxygen, sulphur, and other elementary substances combine with the metals to form ores; but silica (SiO_2) and carbonic acid (CO_2) possess the property of being able to combine with the oxides of the metals, as bases, forming large and varied groups of minerals termed silicates and carbonates respectively. Both are important as rock-forming constituents, the former occupying the dominant place.

Take the case of carbonic acid (carbon dioxide).

Acid.	Base.
Carbonic acid	+lime.
CO_2	+CaO=Calcium carbonate.
Carbonic acid	+magnesia.
CO_2	+MgO=magnesium carbonate.

Carbonic acid may combine with one base, as with lime, forming calcite; or with two bases, forming dolomite, the carbonate of calcium and magnesium.

Carbonate of lime and carbonate of magnesia, in both their crystalline and massive forms, compose rock-masses that are frequently of great extent.

Silica possesses all the properties of an acid, and is hence chemically termed silicic acid. Now silica, unlike carbonic acid, can combine not only with one but with two, three, or more bases in the same compound, giving rise to an exceedingly varied and numerous class of minerals of homogeneous structure and uniform composition.

Thus silica may be combined with—

One base, as in talc, the silicate of magnesia.
Two bases, as in olivine, the silicate of magnesia and iron.
Three bases, as in epidote, the silicate of alumina, lime, and iron.
Four or more bases, as in mica (muscovite), a silicate of alumina, potash, and other bases.

From what has beer said, we see that silica may occur in Nature as—

(1) *Free* or *uncombined*, as in quartz, which is the principal constituent of beach sand and sandstones.
(2) *Combined* with bases such as alumina, lime, magnesia, soda, potash, etc., forming the vast group of minerals termed *silicates*.

PRINCIPAL ROCK-FORMING MINERALS.

A great many minerals enter into the constitution of the crust of the Earth, but the main mass is composed of a few predominating compounds of these:

silica, SiO_2, in its *free* and *combined* conditions constitutes more than half of the known crust.

Alumina, nearly all of which occurs combined with silica, is present to the extent of 15 per cent.

After alumina follow iron oxides, 7·5 per cent.; lime, 5·5 per cent.; magnesia, 4·5 per cent.; soda and potash, each 3 per cent. All of these, except a portion of the iron, exist in the condition of carbonates and silicates.

The principal rock-forming minerals are as follows:—

(1) Quartz.	(10) Nepheline.
(2) Felspar.	(11) Tourmaline.
(3) Mica.	(12) Calcite.
(4) Olivine.	(13) Aragonite.
(5) Serpentine.	(14) Dolomite.
(6) Chlorite.	(15) Fluorite.
(7) Hornblende.	(16) Apatite.
(8) Augite.	(17) Iron ores.
(9) Rhombic pyroxene.	

Primary and Secondary Minerals.—A *primary* mineral or rock constituent is one that is developed during the cooling of the molten magma, or, in the case of a sedimentary rock, that appeared among the original constituents.

A *secondary* mineral is one that appeared after the rock-mass was formed. It is usually a product of the alteration or decomposition of one of the original or primary minerals.

Essential Minerals.—Many kinds of rock are recognised by geologists as being composed of an aggregate of certain minerals. Thus granite, as previously stated, is an aggregate of quartz, felspar, and mica. If any one of these be absent, the rock would not be recognised as a granite; hence these three are spoken of as *essential* minerals.

Accessory Minerals.—These are minerals that may or may not be present in a rock. They are *accessory* because their presence or absence does not alter the constitution of the rock, though, if abundant, they may modify it to some extent. Thus, when tourmaline is present in granite it is merely accessory.

Quartz.—This occurs in both the crystalline and amorphous or chalcedonic forms. It is harder than steel, and therefore cannot be scratched with a knife or file. On account of its great hardness it is frequently the last or ultimate residue of the detritus derived from the denudation of a land area; for while the softer materials are reduced by attrition to the condition of mud either during their transport to the sea or after they reach the sea, the quartz particles manage to survive, although doubtless greatly reduced in size.

These surviving quartz grains, sometimes angular, sometimes semiangular, and frequently rounded in shape, are piled up on sea and lake beaches, forming the familiar sea-sands found on nearly every strand.

When free from impurities, quartz is clear and transparent, but it is frequently pale-grey, pale-yellow, golden-yellow, or reddish-brown in colour owing to the presence of iron oxides. The intensity of colour becomes greater as the percentage of iron oxide increases.

Quartz is the principal constituent of sandstones, and is an *essential* constituent of mica-schist, gneiss, quartzite, rhyolite, and quartz-porphyry. As a *secondary* mineral deposited from slowly moving siliceous waters it occurs, filling cracks, fissures, and cavities. It is frequently developed in igneous rocks as a *secondary* product resulting from the alteration or decomposition of silicates.

Large bodies of quartz in the form of *siliceous sinter* are deposited by thermal springs in many volcanic regions.

Siliceous sinter is deposited in successive layers, and for that reason frequently possesses a banded or laminated structure. When newly formed it is massive or amorphous, but in course of time it develops a crystalline structure.

The principal varieties of crystalline quartz are as follows.—

Rock crystal is a colourless transparent variety much used for spectacle-glasses, lenses, etc.

Amethyst, which is a purple or violet variety often of great beauty It is believed that the colour is mainly due to the presence of manganese oxide

Cairngorm has a fine smoky-yellow or brown colour

Ferruginous quartz possesses a yellow or reddish-brown colour due to the presence of iron peroxide Abundant in many lands

Among the numerous varieties of massive or chalcedonic quartz are.—

Chalcedony, found lining cavities in rocks and as stalactites The colour is often milk-white, yellow, brown, or lavender-blue.

Carnelian, red or reddish-brown

Flint, of various shades from grey to black Occurs as nodules in chalk, and as beds, forming rock-masses

Agate is a variegated and banded chalcedony.

Plasma is a leek-green variety speckled with white.

Heliotrope or *bloodstone* is a leek-green variety speckled with red

Onyx, a banded variety of chalcedony

Chert, a calcareous form of massive quartz, occurs in nodules and beds, and is a rock rather than a mineral

Jasper, a massive or very finely crystalline quartz coloured red, reddish-brown, or yellow by iron oxides In some of the older formations there occur beds of hard, fine-grained, red, or purple siliceous shales and slates, which are generally spoken of as jasperoid shales or jasperoid slates

Among the different forms of hydrous silica are—

Opal, which occurs in great variety ranging from *wood-opal* to the gem *noble opal* Wood-opal is what is familiarly termed silicified or petrified wood It is merely a replacement of wood by particles of hydrous silica

Felspar.—This important family consists of several minerals, which show a close relationship in chemical and physical properties, as well as in their mode of occurrence

Chemically considered, the felspars are silicates of alumina and one or more of the bases potash, soda, and lime

The cleavage of the felspars is specially characteristic, and it enables the different species to be divided into two natural groups, namely—

I *Orthoclase* [1]
II *Plagioclase.*[2]

This subdivision is based on the direction of the cleavage-planes, for, whereas all the felspar minerals show good cleavage in two directions, in *orthoclase* felspar these two directions are at right angles to one another, and

[1] Gr. *orthos*=straight, and *klasis*=breaking.
[2] Gr. *plagios*=slanting, and *klasis*=breaking.

in the *plagioclase* felspars they are slightly oblique. In other words, orthoclase crystallises in the monoclinic crystal-system, and plagioclase in the triclinic.

The distinguishing character of plagioclase is the appearance of fine *lamellæ* (see fig. 139), arising from *polysynthetic* twinning, which is never exhibited by orthoclase.

Orthoclase usually presents dual twinning on various types, the commonest being the Carlsbad. Twinning may often be detected with a hand lens, but is best seen in thin sections viewed in polarised light.

Orthoclase (monoclinic) is typically a silicate of alumina and potash, consisting of silica=64·6, alumina=18·5, and potash=16·9 per cent. When soda replaces the potash we get soda-orthoclase, which is a triclinic felspar. Orthoclase is an essential constituent of granite, gneiss, and syenite, in which it occurs as tabular crystals of a grey, creamy, or pink colour.

Sanidine is a clear glassy variety of orthoclase. It is a common constituent of modern acidic lavas, as rhyolite and trachyte.

Plagioclases or Triclinic felspars. These include two distinct species, *albite*, typically a silicate of alumina and soda; and *anorthite*, typically a silicate of alumina and lime. Between albite which represents the acidic type of plagioclase and anorthite, the basic, there are various mixtures of these two, producing a continuous series of closely related minerals.

Let Ab=albite=$Na_2Al_2Si_6O_{16}$.
An=anorthite=$CaAl_2Si_2O_8$.

Thus the series of plagioclases includes—

Albite[1] (pure)=Ab.
Oligoclase[2] =Ab_6An_1 to Ab_3An_1.
Andesine[3] =Ab_3An_1 to Ab_1An_1
Labradorite[4] (most acid)=Ab_1An_1.
Labradorite (medium) =Ab_3An_4.
Anorthite[5] (nearly pure) =An.

For the most part the plagioclase felspars are constituents of the basic and semi-basic or intermediate types of igneous rocks, and orthoclase, with its glassy variety, sanidine, of the acidic.

Acidic and Basic defined.—An acid or acidic rock or mineral is one in which the silica or silicic acid, SiO_2, in molecular ratio, is in excess of the bases; and a basic rock or mineral is one in which the bases predominate. Take the case of orthoclase. Its composition is—

Silica, ...	64·60 per cent.
Alumina, ...	18·45 ,,
Potash, ...	16·95 ,,
	100·00 per cent.

The silica exceeds the sum of the bases, alumina and potash; therefore this mineral is acid or acidic.

Mica.[6]—The mica family comprises a great many species, all of which occur

[1] Lat. *albus*=white.
[2] Gr. *oligos*=small, and *klasis*=breaking.
[3] From Andes in South America.
[4] From Labrador in North America.
[5] Gr. *a*=without or not, and *orthos*=straight.
[6] Lat. *mico*=I glisten.

in thin flexible plates. The micas are silicates of alumina and other bases. The most important as rock-forming minerals are as follows :—

Muscovite[1] (Potash-mica) occurs in thin transparent plates, and is an essential constituent of granite, gneiss, mica-schist, and many crystalline rocks. It is the white mica of commerce, and in plates over two inches square is of considerable value.

Biotite[2] (Magnesia-mica) is a black mica which is abundant in some granites, gneisses, and schists.

Lepidolite[3] (Lithia-mica) possesses a ruby-red or peach-blossom colour. It is found in some granites and schists.

Sericite is a colourless hydrous mica, produced by the alteration of alkali-felspar. It is also developed by the action of great pressure, and hence is abundant in schists that have been altered by dynamo-metamorphism.

Olivine.—This is a silicate of magnesia and iron. It is an essential constituent of basalt, and forms the main mass of olivine-rock or peridotite ; a rock which in some places occurs in masses of great extent.

Serpentine.—This is the hydrous silicate of magnesia and iron. It frequently forms rock-masses and also occurs in veins and nests in basic igneous rocks. It is an alteration product of olivine or other basic minerals.

Chlorite.—This is a hydrated silicate of magnesia, alumina, and iron which occurs in small dark olive-green scales, or in green earthy aggregates. It is an essential constituent of chlorite-schist, and is quite common as an alteration product of hornblende in igneous and metamorphic rocks.

Hornblende.—This is a silicate of magnesia, lime, alumina, and other bases. It includes a great many varieties, which are arranged in two groups—

(1) Aluminous=brown or black varieties.
(2) Non-aluminous=pale-green and grey fibrous varieties.

In a general way it may be said that the dark hornblendes affect semi-basic rocks, such as diorite and andesite ; and the pale green fibrous varieties acidic rocks, such as gneiss.

The dark varieties also form rock-masses, as in the case of hornblende-schist and amphibolite.

Hornblende is an essential constituent of syenite, diorite, and hornblende-andesite, but it occurs abundantly as an alteration product of augite.

The name *amphibole*[4] is frequently used as a family name to include all the varieties of hornblende.

Augite.[5]—A variable silicate of lime, magnesia, alumina, iron, and manganese. It includes many varieties, which are generally grouped under the family name *monoclinic pyroxene.*

Like hornblende, the augites fall into two natural groups, namely—

(1) Aluminous=dark varieties, including common augite.
(2) Non-aluminous=green varieties.

The green varieties are found abundantly in metamorphic rocks, as gneiss, crystalline limestone, and various schists ; and the dark or aluminous varieties,

[1] From Muscovy.
[2] From Biot, the French mineralogist.
[3] Gr. *lepis*=a scale, and *lithos*=a stone.
[4] Gr. *amphibolos*=ambiguous.
[5] Gr. *auge*=lustre.

in rocks of a basic type, as basalt, diabase, and andesite. The clear-green variety *diallage* is found in serpentine and gabbro.

Rhombic Pyroxenes.[1]—These are variable silicates that occur abundantly in many basic igneous rocks. The most common varieties are *enstatite*, *bronzite*, and *hypersthene*, the former being plentiful in serpentine and olivine rocks.

Nepheline.[2]—A silicate of alumina and soda with some potash. This is an important constituent of alkali volcanic rocks. It is always present in phonolite, and is also found in some basalts.

Some greenish and reddish massive varieties of nepheline, known as *elæolite*,[3] occur in some syenites and ancient crystalline rocks.

Tourmaline.[4]—A silicate of alumina, iron, and other bases. Colour generally black, but green and red varieties are not uncommon. Frequently occurs in long well-developed hexagonal prisms.

Tourmaline commonly occurs in granites, gneisses, schists, and crystalline limestones. With quartz it forms tourmaline-rock. This mineral is the nearly constant associate of tin ore.

Calcite ($CaCO_3$).—This is the principal constituent of all limestones. It is present in many shales and sandstones. As a secondary product resulting from the alteration of silicates containing lime, calcite is found filling cracks, fissures, and cavities in many igneous and crystalline rocks.

It is deposited by water in caves, forming *stalactites* which hang from the roof, and *stalagmites* which grow up from the floor.

The soft, spongy, or porous variety deposited by water at the foot of limestone cliffs and in rock-shelters is a calcareous sinter known as *travertine*.

Aragonite[5] ($CaCo_3$).—This is the rhombic form of carbonate of lime. It composes the shells of many molluscs, but is a less stable compound than calcite. It is not abundant, being usually found in thin veins in basalt and other igneous rocks. The fibrous variety is often very beautiful.

Dolomite[6] (Carbonate of lime and magnesia).—This forms extensive beds of massive magnesian limestone belonging to many different geological formations. It also occurs in small quantity as an alteration product of ordinary limestone and aragonite.

Fluorite (Fluoride of calcium=*fluor spar*, CaF_2).—This usually occurs as the gangue or matrix of lead and zinc ores.

Apatite.[7]—This is the phosphate of lime with a little fluoride or chloride of calcium. It occurs in large crystals and as massive deposits in metamorphic rocks. Minute needles are common in many granites, schists, and basalts.

Iron Ores.—Iron in its various forms is one of the most widely distributed of all the substances that enter into the structure of the Earth's crust, being found in rocks of all kinds and all ages. It occurs combined with silica in many rocks and rock-forming minerals, and also as separate compounds of oxygen, sulphur, etc., forming what are termed ores of iron.

Silica combines with the protoxide of iron and other bases, forming silicates. The indistinct green or bluish-green colour which is so prevalent in all classes of rock is commonly due to the presence of iron. When such rocks weather or become decomposed, the silicates are frequently broken up owing to the removal of one or more of the bases. The iron protoxide, FeO, being liberated,

[1] Gr. *pŷr*=fire, and *xenos*=a stranger.
[2] Gr. *nephele*=a cloud.
[3] Gr. *elaion*=oil.
[4] Turamali, the Singhalese name of the mineral.
[5] Aragon, a province of Spain.
[6] Named in honour of the French naturalist, Dolomieu.
[7] Gr. *apatao*=I deceive.

changes or oxidises into the peroxide, Fe_2O_3, which possesses a red or rusty-brown colour. Thus it comes about, as we so frequently find, that rocks which possess a pale-green colour in the fresh undecomposed portions, become red or rusty-brown on weathered surfaces, or even produce brick-clays that are yellow or reddish-brown.

The most abundant natural compounds of iron are as follows :—

Native iron, found in meteorites and serpentine alloyed with nickel.
Iron protoxide, FeO, not in free state, but combined with silica in many silicates.
Magnetite, Fe_3O_4, the black magnetic oxide.
Hæmatite, Fe_2O_3, the red peroxide, *i.e.* highest oxide.
Limonite or brown hydrous peroxide.
Pyrite, FeS_2, the yellow sulphide.
Marcasite, FeS_2, the white sulphide.
Pyrrhotite, Fe_7S_8, the magnetic sulphide.
Titanite (Titaniferous iron), a black, feebly magnetic mineral.
Glauconite, a dark-green hydrous silicate of magnesia and iron.

Magnetite.—This mineral is commonly found in igneous and crystalline rocks. It occurs in thick beds, irregular masses frequently of great extent, and as small grains disseminated throughout many igneous and altered rocks. In rocks subject to weathering it changes first to the carbonate and then to the brown or red peroxide. Hence sands, gravels, and compact rocks containing magnetite soon assume a rusty-brown colour on the surface when exposed to the action of air and water.

Hæmatite.[1]—This valuable ore of iron occurs as beds interstratified with sedimentary and schistose rocks, and as a constituent of many mineral veins.

Limonite.[2]—This ore occurs in beds and irregular deposits in stratified formations, and as the *gossan* or *cap* of sulphide lodes. In the form of *bog-iron* it is frequently found as irregular sheets on the lake-bottoms and in marsh lands where it has been deposited by the action of organic acids or iron bacteria.

This is the oxide of iron which gives the prevailing yellow or rusty-brown colour to soils, clays, sands, and many sandstones.

Pyrite.[3]—This mineral is present in the majority of gold, silver, copper, and other mineral veins. It also occurs as disseminated crystalline grains in slates, and many varieties of schistose rock. As a secondary product it is frequently abundant in altered andesites and other igneous rocks. It is also common as nodules and pseudomorphs in clays and shales. Pyrite in its crystalline form is a very stable compound, being hardly affected by atmospheric oxidising agents even after long exposure.

Marcasite.[4]—This is the rhombic form of iron disulphide. It is quite common in clays, shales, coal, and all stratified formations, also in mineral veins. It decomposes rapidly when exposed to moist air, liberating free sulphuric acid which at once attacks the minerals with which it comes in contact, forming alum, gypsum, or other sulphates.

Pyrrhotite.—This mineral is not so widely distributed as pyrite and marcasite. It occurs mostly as grains and masses, impregnating metamorphic or crystalline rocks.

Titanite.—This composes the black titanic iron-sand found on many sea-

[1] Gr. *haima*=blood.
[2] Fr. *limon*=mud.
[3] Pyrites, an old Greek mineral-name, which comes from *pŷr*=fire.
[4] Margashitha, an Aramean foreign word, used by the Arabians (name of a mineral).

beaches. It occurs as scattered grains and plates in many igneous and metamorphic rocks. It is a very stable compound, and for that reason is able to resist weathering for a long time without alteration or oxidation.

Glauconite.—This is an important constituent of many sandstones and limestones to which it frequently imparts a characteristic green colour. It is found filling and coating foraminifera and other minute organisms, and is usually believed to have an organic origin. Glauconitic greensands are prevalent in Cretaceous and Lower Tertiary marine rocks in all parts of the globe, but are unknown among the Palæozoic formations. It is probable that most of the valuable aggregations of iron-ore associated with the more ancient altered sedimentary rocks are composed of iron segregated from Palæozoic glauconitic sandstones and limestones.

CHAPTER XIV.

SEDIMENTARY ROCKS.

A ROCK may be composed of one or more simple minerals, or it may be a mechanical aggregate of particles derived from pre-existing rocks.

Classification of Rocks.—Rocks may be grouped in two great natural classes, namely—

I. *Sedimentary or Aqueous.*
II. *Igneous.*

The altered forms of sedimentary and igneous rocks constitute a third class—

III. *Metamorphic.*

The grouping of rocks as *Sedimentary* and *Igneous* is purely genetic and therefore based on a scientific principle. The class *Metamorphic* does not possess the same value, as it merely comprises altered forms of rocks that, in their unaltered condition, are included in the other two classes. Its use, however, may be defended on the grounds of expediency and convenience.

Sedimentary Rocks.

Sedimentary rocks, as the name implies, are composed of sediments that were laid down by the agency of water; hence the equivalent name *Aqueous* so frequently applied to them. They are also called *Clastic* or *Fragmentary*, but the second of these is open to the objection that many masses of igneous rocks are fragmentary. but in no sense sedimentary or aqueous.

Sedimentary rocks that are composed of material derived from the denudation of pre-existing rocks are said to be *detrital*; that is, *mechanically formed.* Those formed by the accumulation of organisms, either calcareous, siliceous, or carbonaceous, are termed *organic*; while the minerals that accumulate on the floor of lakes and inland seas as the result of chemical precipitation or evaporation are called *chemical.*

Here we have a basis for a threefold subdivision of sedimentary rocks—

1. **Detrital.**
2. **Organic.**
3. **Chemical.**

These three groups are further subdivided as under—

1. Detrital { (a) Arenaceous [1]—Sandy and pebbly rocks.
(b) Argillaceous [2]—Clays and shales.

[1] Lat. *arena*=sand. [2] Lat. *argilla*=clay.

2. Organic
- (*a*) Calcareous [1]—Limestones.
- (*b*) Siliceous [2]—Cherts and flints.
- (*c*) Carbonaceous—Coals.
- (*d*) Ferruginous [3]—Ironstones.

3. Chemical
- (*a*) Carbonates—Limestones.
- (*b*) Sulphates—Gypsum.
- (*c*) Chlorides—Rock-salt.
- (*d*) Silica—Siliceous sinter.

Detrital Group.

Arenaceous Rocks.

The main types of rock included in this group are—

1. Breccia.
2. Conglomerate.
3. Sandstones and gritstones.

Breccia.[4]—This is a rock composed of angular fragments of stone cemented in a paste of sand or mud, or set in a matrix of carbonate of lime, silica, or oxide of iron (Plate XV.).

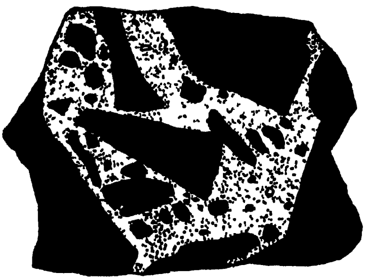


Fig. 115.—Showing breccia. (After Davis, *U.S. Geol. Survey.*)

Breccias were formed in places where frost-formed screes or talus-slides descended into sheltered bays or lake-basins in which the material was spread out near the shore without being subjected to the wear and tear or sorting action of rapidly moving currents.

Breccias, from the nature of their formation, may sometimes attain a great thickness, but they seldom cover an area of large extent. Some breccias exhibit a rude stratification, and in places where they have accumulated slowly they may even contain fossils. As a rule, however, they are not fossiliferous.

Many breccias contain a variable proportion of water-worn material, and some are known to pass in the same plane into coarse conglomerate.

A breccia composed principally of angular slaty fragments is called a *slaty breccia*; of sandstone, a *sandstone breccia*; of mica-schist, a *mica-schist breccia*; of quartz, a *quartzose breccia*, and so on.

The fragments composing a breccia may range from less than an inch to many feet in diameter.

Not infrequently a bed of very coarse breccia riding hard on an old shore-line is found at the base of a conglomerate. Such a breccia may contain angular masses of rock ten feet or more in diameter, torn from the bed-rock on which it rests. Such a deposit would appear to have been formed by the undercutting of steep sea-cliffs, at the foot of which the water was too deep for the fallen blocks to be subjected to the pounding and rounding effects of wave-action.

Moraine-breccias have been formed where the angular ice-borne material was shot into a lake, estuary, or fiord; or left when the ice melted.

Fault- or *Friction-breccias* are frequently found on the walls of great faults

[1] Lat. *calx*=lime. [2] Lat. *silex*=flint. [3] Lat. *ferrum*=iron.
[4] It. *breccia*=a crumb (pronounced bréchia).

Quartzite and Chert Breccia, Utah. (U.S. Geol. Survey.)

Moreover, a conglomerate may contain rocks that have appeared as constituents of different formations. Thus, in the King County of Auckland there is a coarse conglomerate at the base of the Lower Tertiaries mainly composed of granite, gneiss, and crystalline schists derived from a still coarser conglomerate interbedded with the neighbouring Triassic rocks.

Conglomerates, as might be gathered from the manner in which the original gravels were formed, thin out rapidly when traced seaward from the old strand. They are frequently intercalated with tapering beds of sandstone and shale.

What are called *crush-conglomerates* are sometimes found on the walls of powerful faults. They consist of large fragments of wall-rock that have become more or less rounded, polished, and sometimes striated with the rolling and kneading action to which they have been subjected during the fault-movements. The boulders are usually embedded in a matrix of stiff clay composed of crushed rock. The origin of a crush-conglomerate is purely dynamical.

Sandstones and Grits.—Sandstones are merely consolidated sands.

River and sea-sands are principally composed of quartz grains, but the composition of the sand in any given locality depends principally on the nature of the country from which it is derived.

Sands derived from the denudation of granite, gneiss, mica-schist, or sandstone consist mainly of quartz frequently associated with a small amount of magnetite, rutile, zircon, garnet, and tourmaline. If the sands occur in a situation where they have not been subjected to much attrition by wave-action or sea-currents, they may contain a small percentage of mica and orthoclase. The so-called *black sands* of many beaches are principally composed of magnetite and quartz grains, the prevalence of the magnetite in places being due to its concentration by the laving action of the advancing and retreating tides.

Sands derived from volcanic rocks frequently contain a considerable proportion of titanic iron and magnetite, and in some cases olivine, augite, and hornblende.

In a general way it may be said that the sands resulting from denudation are the residues of the hardest rock-components in the region. Quartz is at once the hardest and most abundant of all the rock-forming minerals, and for these reasons it is the principal constituent of nearly all sands.

Sand grains are not always quartz or other simple mineral. In many coarse sands they are found to consist of small rock-particles. This is particularly the case in desert sands, which often consist mainly of comminuted rock. And whereas in water-formed sands quartz is the principal constituent in the majority of sands, comprising over 95 per cent. of the total volume, in desert sands, while still the dominant constituent, it is frequently accompanied by considerable amounts of felspar, olivine, augite, hæmatite, and other minerals that could not survive the wear and tear to which sea-borne sands are exposed.

The cementing medium or matrix of sandstones may be carbonate of lime, silica, oxide of iron, or clay.

Carbonate of lime forms *calcareous sandstones.*

Silica forms *siliceous sandstones.*

Oxide of iron (limonite) forms *ferruginous sandstones.*

Clay as a matrix forms *argillaceous sandstones.*

When the iron-oxide matrix occurs in large quantity, the rock is sometimes called a *limonitic sandstone*; and in places where the iron oxide is present in large excess, the rock may pass into an *ironstone.*

In the majority of sandstones the grains are rounded, but in some arenaceous rocks they are subangular or angular.

The colour of sandstones is usually due to the presence of some oxide of iron

which may impart straw-yellow, yellowish-brown, dark-brown, red and green hues according to the degree of oxidation and hydration.

Glauconitic sandstones, usually called *greensands*, are composed of quartz grains coated with the mineral glauconite,[1] or of glauconite grains that are frequently the internal casts of foraminifera.

Glauconite, which is a hydrous silicate of iron with potash and other bases, is found filling or coating foraminifera and other marine organisms on the sea-floor off the coast of South Carolina. It possesses an olive or blackish-green colour, and hence imparts a characteristic green colour to marls, limestones, and sandstones, in which it occurs.

A sandstone containing much mica may be described as a *micaceous sandstone*, and one charged with carbonaceous matter, a *carbonaceous sandstone*.

Sandstones that split easily into thin slabs are called *flagstones* ; while those that possess no distinct bedding are frequently spoken of as *freestones*.

Many of the more ancient sandstones contain a considerable amount of felspar, and are called *felspathic sandstones* or *greywacke*, to which reference is made further on.

Calcareous, argillaceous, and ferruginous sandstones are usually soft and easily cut into blocks ; the greywackes are hard and frequently much jointed and broken ; while siliceous sandstones, which consist of quartzose sand set in a siliceous matrix, are intensely hard and brittle.

The sands of which sandstones are composed were laid down in a river-bed, or on the floor of some estuary, sea, or lake. Hence the character of the contained fossils will be a record of the local conditions of deposition. Thus marine shells will indicate deposition in the open sea ; estuarine shells and the remains of land plants, estuarine or deltaic conditions ; freshwater shells and freshwater fishes with plant remains, lacustrine conditions.

Some sandstones exhibit fine examples of false-bedding, while those of a felspathic character sometimes show a tendency to weather in spheroidal forms, the partings of the different layers being marked by iron-stained seams.

Among well-known examples of sandstones we have the Colley Sandstone (Surrey), of which Windsor Castle is built ; the Stanley Sandstone of Shropshire, used for grindstones and bridge-building ; the Brunton Sandstone of Yorkshire ; the Craigleith Sandstone of Edinburgh ; and the Old Red Sandstone of Scotland. Some well-known sandstones elsewhere are—

The *Desert* Sandstone—Queensland.
The *Grampian* Sandstone—Victoria.
The *Hawkesbury* Sandstone—New South Wales.
The *Cave* Sandstone—Cape and Orange States.
The *Forest* Sandstone—Rhodesia.
The *Beacon* Sandstone—South Victoria Land, Antarctica.

Grits, or *gritstones* as they are sometimes called, are composed of coarse angular grains usually cemented in a matrix of silica or limonite.

Gritstones composed of material derived from disintegrated granite are frequently difficult to distinguish from the parent rock, particularly when they rest directly on it.

A gritstone composed of quartz grains is called a *quartzose gritstone* ; and one that contains besides quartz a considerable proportion of felspar, slate, and felspathic material, constitutes a *greywacke*.

Many Palæozoic and Lower Mesozoic sandstones are greywackes. They appear to be formed of detritus derived from the denudation of land surfaces

[1] Gr. *glaukos*=sea-green.

in which igneous rocks largely prevailed. When fine-grained they are sometimes difficult to distinguish from igneous rocks as seen in the field.

Greywackes frequently alternate with shales and conglomerates. They are found of all degrees of texture from fine-grained to coarse gritty rocks that sometimes approach a breccia in texture. The prevailing colour is a dark greenish-grey, but pale-green and purple varieties are common among the Palæozoic formations. Some of the grey and green varieties are in places brecciated with peculiar thin angular flakes or splinters of dark slate.

Argillaceous Rocks.

The fine sediments resulting from the decomposition of silicate minerals are mainly composed of hydrous silicate of alumina, which in its pure state is known as *Kaolin* or *China-clay*. The majority of clays are not pure, but contain more or less admixture of rock-flour, resulting from the mechanical erosion of rocks by glaciers, running water, or wave-action.

The fine sediments laid down on the sea-floor and in estuaries and deltas is usually called *mud*. Hardened mud may form massive beds of mudstone that possess no lamination, but more commonly it is finely banded with thin layers or laminæ that easily split apart, forming what is geologically called *shale*.

The muds, of which shales and mudstones are composed, were, as a rule, laid down in deeper water than the sands of sandstones. When traced landward, muds graduate into sands, and in the seaward direction pass into calcareous ooze.

A clay rock that does not split into thin layers, but occurs in more or less massive beds, is often called an argillite.

Clay rocks when hardened by compression and cleaved by pressure are converted into *slates*.

A slate in which *mica* has been developed by pressure and molecular change is called a *micaceous slate* or *phyllite*.

Thus, according to the degree of hardening and altèration, we get a series of argillaceous rocks, beginning with muds and clays, that pass progressively into shale, slate, and phyllite.

Slates, shales, and marly clays that have been invaded by igneous dykes are sometimes changed into an intensely hard, brittle, fine-grained black rock called *Lydian Stone*.

Muds containing from 5 to 20 per cent. of carbonate of lime form *marls* or *marlstones*. A sandy shale is called an *arenaceous shale*, while one in which there is present sufficient carbonaceous matter to be easily distinguishable is spoken of as a *carbonaceous shale*. A shale containing bituminous matter forms an *oil-shale*. When a shale contains easily recognisable scales of mica, we get a *micaceous* shale.

Clays, marls, shales, and slates frequently contain fossils which, in the last two, may be flattened and distorted by pressure. In many shales the fossils are replaced by pyrite. The shales associated with coals are usually of estuarine or deltaic origin, and hence frequently contain an abundance of plant remains, impressions of leaves being in many cases beautifully preserved along the lamination planes.

Loam is a mixture of sand and clay. Most loams are of alluvial origin, and for that reason are mostly found on the floor of river-valleys.

Boulder Clay, or *Till* as it is called in Scotland, is a more or less gritty, subglacial clay frequently crowded with angular and subangular blocks of

stone. It varies greatly in composition, even within the limits of a small area. In one place it may be clayey, in another sandy; or again it may pass with startling suddenness into gravelly beds.

Fuller's Earth is a greenish-brown, greenish-grey, bluish or yellowish soft earthy mineral with a greasy feel. Like kaolin, it adheres to the tongue, and when placed in water it falls into powder, but does not form a paste. It possesses great absorbent properties which enable it to remove grease and oily matters from cloth; hence its name Fuller's Earth.

China-clay or *kaolin* and *pipe-clays* are usually found in the neighbourhood of granitic masses, the hydrous silicate of alumina of which they are composed having been liberated by the decomposition of the felspar (orthoclase). They are concentrated by the rain and streams into layers and beds. Occasionally they are found as veins filling rock-fissures.

The underclays of many coal-seams are often found to be almost free from lime, alkalies, and iron and other fusible bases. Hence they possess great fire-resisting properties, being what is termed *refractory*. Such clays are called *fire-clays*. They are ancient soils from which the lime and alkalies have been exhausted by the coal-vegetation.

Gannister is a close-grained, highly siliceous variety of fire-clay found in the Lower Coal Measures of North England. It is of great value for the manufacture of gas retorts and furnace linings.

Brick-clays are impure clays, in many cases resulting from the decomposition of rocks *in situ*.

Laterite[1] is a reddish-coloured ferruginous clay found in many tropical and subtropical lands. It is formed by the subaerial decomposition of rocks *in situ*, especially in flat, low-lying jungle lands where the drainage is feeble. The decomposition of the rock is accomplished by the removal of the silica and the concentration and oxidation of the iron. Considerable deposits of laterite occur in the basalt covered areas of the Deccan. When dried, it frequently forms hard surface layers sometimes called *clay-pans*.

Loess.—The finer particles of subaerial denudation when spread out on river-beds soon dry, and in this condition are easily transported by prevailing winds which deposit their load as a sheet of variable thickness over hill and dale.

Glacial rivers, as a rule, carry a large amount of fine rock-flour in suspension, and when they overspread their banks during the periodical spring and summer floods, the retreating waters leave a thin sheet of silt behind them. When dry this fine sediment is carried far and wide by the wind. When the summer north-west winds blow down the glacial river gorges of Otago and Canterbury, the river-beds and mountain slopes are sometimes completely obscured for many days in succession by an impenetrable cloud of dust. The same phenomenon is reported from Alaska.

Vast sheets of loess occur in Central Europe, North America, and along the courses of the Ganges, Brahmaputra, and Indus, where they cover 300,000 square miles of territory.[2] But perhaps the widest sheets of loess occur in China, where they cover an area of 400,000 square miles.[3]

Mechanically considered loess is a mixture of silt and fine silt.[4] Many

[1] Lat. *later*=brick.

[2] "Manual of Geology of India, Stratigraphical and Structural," *Geol. Surv. of India* 2nd ed., p. 427.

[3] Von Richthofen, *China*, Band 1, p. 56; also *Geol. Mag.*, 1882, p. 293.

[4] See papers by J. A. Udden, *Jour. Geol.*, vol. ii., 1894, p. 323; G. P. Merrill, *Rocks, Rock-weathering, and Soils*, New York, 1906; R. Speight, *Trans. N.Z. Inst.*, vol. xl., 1908, p. 33, and vol. xlix., 1917, p. 386; L. J. Wild, *Trans. N.Z. Inst.*, vol. li., 1919, p. 286.

explanations have been suggested as to its origin. Generally it is believed to be an æolian deposit.

The minerals which compose the loess are quartz, felspar, mica, augite, etc. The quartz prevails by far. These minerals form particles, which are much finer than those of ordinary sand, and are sharply angular and show no sign of rounding by wear. The most characteristic feature of the loess is the content of carbonates of lime and, in smaller quantity, of magnesia. By weathering these carbonates are destroyed and the loess becomes a loam. The colour of fresh loess is yellowish-brown, that of the weathered loess or loess-loam dark-brown.

ORGANICALLY FORMED ROCKS.

(*a*) Calcareous.	(*c*) Carbonaceous.
(*b*) Siliceous.	(*d*) Ferruginous.

Calcareous Rocks.

The rocks of the Calcareous group are essentially composed of carbonate of lime. The principal varieties of limestone are—

1. Coral limestone.
2. Polyzoan limestone.
3. Archæocyathinæ limestone.
4. Nullipore limestone.
5. Foraminiferal limestone (Chalk).
6. Crinoidal or Encrinital limestone.
7. Shell limestone.
8. Ostracod limestone.
9. Annelid limestone.
10. Freshwater limestone.

ORGANICALLY FORMED LIMESTONES.

The organisms principally concerned in the forming of limestones are corals, hydrozoans, calcareous algæ, both freshwater and marine Polyzoa, Foraminifera, crinoids, calcareous annelids, Ostracod crustaceans, and molluscs.

Coral Limestones.—Many corals are single, and live as separate individuals or in clusters. Others live in colonies and build reefs. The single corals can live at a considerable depth, and they range into the colder seas of subtropical latitudes. On the other hand, the reef-building corals are confined to tropical seas where the temperature does not fall below 68° F., and they are unable to live at a depth exceeding thirty fathoms.

Corals first made their appearance in the Ordovician period, and since that time they have played an important part in the structure of many limestones, both as assemblages of single corals and as reef-builders.

Among the limestone-forming corals of the Ordovician are the genera *Halysites*, and *Heliolites*; of the Silurian, *Halysites*, *Heliolites*, and *Favosites*, all abundant in the Wenlock Limestone, and contemporary limestones in America, Russia, China, New South Wales, Queensland, Victoria, and Tasmania.

Corals take a large share in the formation of the Devonian limestones of Europe, America, and Australia. In Queensland the Burdekin Lower Devonian coralline limestone attains a thickness of 7000 feet, the most abundant corals being *Heliolites*, *Favosites*, and *Alveolites*. The Peak Down coralline limestone in the same State is mainly composed of the coral *Cyathophyllum*. The Devonian Murrumbidgean and Lambrian series of New South Wales are intercalated with thick beds of coralline limestone in which *Heliolites*, *Favosites*, *Cyathophyllum*, and *Diphyphyllum* are among the most common forms.

The Lower Carboniferous limestones of Europe and America are mainly composed of

corals, with which are associated many crinoids and brachiopods. Of the corals, the genera *Lithostrotion*, *Lonsdaleia*, *Clisiophyllum*, *Cyathophyllum*, and *Syringopora* are the most important.

The Permian was dominantly a period of continental conditions of deposition, and in consequence calcareous members are feebly developed. These conditions came into existence before the Permian, and as a result the Permo-Carboniferous rocks of India, New South Wales, South Africa, Brazil, Falkland Islands, and North America are mainly of the continental facies, distinguished by a flora of a specialised type. Calcareous members are present in the New South Wales coal-bearing series, but they are subordinate to the freshwater and continental beds, and coral genera are relatively scarce, the most prominent being *Trachypora*, which occurs abundantly in the Upper Marine Series. The Isle of Timor in the Moluccas has yielded Permian marine calcareous deposits with a very rich content of ammonites, lamellibranchs, brachiopods, crinoids, blastoids, and corals. Other marine deposits of Permian age occur in Sicily and in the Alps, etc.

The Triassic rocks of Europe were, in part, of continental origin. In the Alpine Trias limestones occur abundantly, but corals are rare.

The general subsidence that set in during the Rhætic introduced marine conditions in the Jurassic, but the sediments were mostly laid down in shallow muddy seas that did not favour the existence of coral life. The limestone bands intercalated with the clayey rocks of the Lias are not coral reefs like the limestones of the Silurian and Carboniferous systems, nor are they often shell-banks. Most of the bands appear to be composed of calcareous muds, derived from the denudation of Palæozoic limestones, and in consequence are seldom pure, but almost always argillaceous or ferruginous. Though limestones are numerous in the Oolite of England, they are not coralline. In structure they are usually oolitic or pisolitic, and as a rule conspicuously current-bedded. They are composed either of detrital calcareous mud, or of chemically precipitated carbonate of lime.

Coral limestones are not common in the Cretaceous, or in any part of the Tertiary till we come to the raised coral limestones of Pliocene and Pleistocene age in the tropical islands of the Pacific and Indian Oceans.

Polyzoan Limestones.—Like the reef-building coral polyp, Polyzoa live in colonies and build up a cylindrical or frond-like framework which is usually composed of carbonate of lime.

In the new environment ushered in with the Permian, the marine fauna was scanty, but a few forms appear to have survived and multiplied. The Polyzoa, which first appeared in the Ordovician, now became exceedingly numerous and formed masses of limestone.

In the Upper Cretaceous Polyzoa are numerous; in the Miocene of France, Austria, Italy, and New Zealand they grew in reef-like masses. The Oamaru limestone of Otago, Mount Gambier limestone, South Australia, and Point Turton limestone, Cape Yorke (S. Aust.) are Miocene polyzoan reefs.

Archæocyathinæ Limestones.—The Archæocyathinæ comprise a small group of cup-shaped organisms that cannot be placed in the zoological series. They are typically represented by the calcareous genus *Archæocyathus*, which somewhat resembles a simple rugose coral, and is considered by Hinde to be related to the Madreporarian corals. The limestone bands in the lowest Cambrian strata (*Olenellus* Beds) of the United States and Canada are largely composed of these peculiar forms which are among the most ancient of all known fossils. They are also abundant in the lowest Cambrian rocks of Spain and Sardinia. In the Cambrian Sea of South Australia, from Normanville to the northern limits of the Flinders Ranges, there existed a great reef, at least 150 feet thick, composed almost exclusively of these organisms.[1]

Coralline and Nullipore Limestones.—Certain marine Algæ secrete carbonate of lime for the construction of their framework; and some of them, such as the Corallines, Nullipores, and the *Dactyloporidæ*, are capable, singly or in combination with other calcareous organisms, of forming limestone masses, sometimes of great extent.

The Corallines are exceedingly abundant in the existing seas, and often play an important part in the structure of modern coral reefs. Little is known of their occurrence in the fossil state.

The Dactyloporidæ appear in the Palæozoic limestones, but the most famous deposit formed by Algæ of this group is the massive *Gyroporella* limestone of the Bavarian and Tyrolese Alps, of Triassic age. The genus *Gyroporella* also forms limestone bands in the Cretaceous series of the Southern Lebanon Mountains.

Limestones composed more or less of Nullipores (*Lithothamnium*) occur in the Mesozoic rocks of Europe and India, and are extensively developed in Tertiary strata. Perhaps most notable among these is the Eocene Nulliporenkalk, or Leithakalk, of the Vienna Basin, which attains a great thickness and extends from Austria, through the Balkans, to Asia Minor and Persia. The Tertiary Nullipore limestone of Algeria is also a massive deposit that, like the

[1] W. Howchin, *The Geology of South Australia*, Adelaide, 1918, p. 188.

Leithakalk, probably grew as a barrier reef in the Central Sea, Tethys. At Tickera, in South Australia, a Nullipore limestone 15 feet thick forms the sea-cliffs, and extends across Cape Yorke Peninsula to Kulpara.[1] The Nullipores, *Lithothamnium* and *Halimeda*, are second only to the coral polyp as modern reef-builders.

Foraminiferal Limestones.—The tests of the calcareous Foraminifera are among the most important of rock-forming organisms. The Foraminifera first appear in the Ordovician, and become numerous in the Ordovician and Silurian, but, so far as known, they do not constitute a prominent part of the limestones of these periods. Beginning with the Carboniferous, these minute Protozoans are more or less abundant in all the later formations, and sometimes exist in such numbers as to form a rock that may be called a Foraminiferal limestone. Of this nature are the *Saccammina* limestone of Northumberland, the *Fusulina* limestones of Russia and Asia, and *Endothyra* limestone of North America, all of Carboniferous age.

In the Mesozoic era, Foraminifera are sometimes present in sufficient numbers as to form limestones. It is in the Cretaceous period that the greatest development of the Foraminifera takes place.

White Chalk is mainly made up of the entire or broken shells of Foraminifera, among which the genus *Globigerina* plays a dominant part. As already described, this genus composes the greater part of the Globigerina ooze of modern seas.

Throughout the Tertiary, Foraminifera are present in great abundance, and form massive beds of limestone. Notable among these are the Eocene nummulitic limestones of Western and Southern Europe, Egypt, and India, composed almost entirely of the disc-like *Nummulites* (fig. 152).

Crinoidal or Encrinital Limestones.—Of the Echinodermata only one order becomes important as a rock-builder, namely, the Sea-lilies or Crinoids. Broken and rolled fragments of Crinoids are abundant in some Ordovician and Silurian limestones; and in the Devonian and Carboniferous periods they form the greater part of thick beds of limestone. Crinoids compose some Mezosoic limestones with exclusion of any other material.

Shell Limestones.—The shells of Molluscs have accumulated so as to form beds of limestone in all the great periods, from the Ordovician upwards. Some shell-limestones are composed of a great assemblage of genera; others are formed mainly of a single genus. Oysters that grew in place are conspicuous in many parts of the younger formations, and the peculiar *Hippurites*, that also flourished on shallow banks, was so numerous in the Cretaceous Mediterranean Sea of Southern Europe as to form massive beds of limestone.

In other cases, limestones have been formed by the slow accumulation of deep-sea, or pelagic, molluscs, which live at or near the surface of the sea, but fall to the bottom on death. The Pteropodal ooze of the present-day deep-sea, and the Pteropodal limestones associated with uplifted coral reefs, are typical of this class of deposit. Pteropodal limestones are known as old as the Devonian, but are rare and always thin. A good example is the Devonian Pteropodal limestone of Canandaigua, United States.

Ostracod Limestone.—The Ostracoda are small crustaceans enclosed in a bivalve shell. Some are freshwater, others marine. They are known in all the great formations from the Cambrian to Recent. In some periods they were so numerous as to form thin bands of limestone.

Annelid Limestones.—Only in exceptional cases do annelids play a conspicuous part in rock-building, though the calcareous annelids may sometimes contribute clusters or colonies to the mass of a limestone mainly composed of other organisms. The worm *Serpula*, which lives in single tubes, or in colonies of parallel tubes, is present in all modern coral reefs.

Freshwater Limestones. — These are composed of freshwater organisms that secrete carbonate of lime for the framework of their skeleton. Their remains accumulate as a slimy ooze on the floor of lakes; and deposits of considerable extent are often met with on the sites of extinct lakes. By the dissolution of the carbonate of lime by water percolating through the deposit, followed by re-deposition, the deposit is sometimes altered into a compact rock.

Prominent among the organisms that form freshwater calcareous deposits is the alga *Chara*, the nucleus of which is calcareous. Other sources of calcareous matter are the shells of freshwater molluscs, as *Unio*, which often occurs in great abundance, and the Ostracod crustaceans. Lacustrine limestones of Tertiary age occur in all parts of the globe. They are, as a rule, thin, and of small extent. The well-known Oligocene Bembridge Limestone in the Isle of Wight contains an abundance of *Chara* remains.

Crystalline Limestone or Marble.—In this rock the original organic structure has been completely obliterated by the development of a granular, crystalline structure. Crystalline limestones are found in stratified formations of nearly all ages, but are particularly prevalent in the older Palæozoic systems. They vary in colour from the finest white statuary marble of Carrara in Italy to the dark mottled and veined varieties found in Ireland. Some of the

[1] W. Howchin, *loc. cit.*, p. 190.

ancient limestones contain grains and nests of graphite occurring throughout the whole mass or confined to certain horizons of the rock.

Argillaceous Limestone.—Earthy or chalky limestones containing a considerable proportion of clayey matter constitute what is termed an *Argillaceous* or *Hydraulic Limestone.* The constituents of this rock are such that when it is calcined and pulverised, the resulting powder forms a natural cement which possesses the property of setting under water; hence the name *hydraulic cement.*

Æolian Limestones.—Beach quartzose sands are sometimes carried far inland by the wind and spread out in layers. When these deposits become consolidated by the infiltration of waters that dissolve the iron-bearing minerals and redeposit the iron as the hydrous oxide, they form limonitic sandstones.

It is recognised that in certain conditions sands and dust composed mainly of minute calcareous organisms, and dried coral-mud, may be spread far inland by the wind, and like ordinary beach-sands may form stratified and cross-bedded deposits of considerable size.

On the island of Bermuda, where siliceous material is entirely wanting, the coastal dunes are composed entirely of calcareous material, consisting mainly of the remains of Foraminifera, coral-sand, and fragments of shells. The older deposits by the infiltration of water have been consolidated into a hard rock called *anemocalcarenyte* or *Bermudaite.* Æolian limestones, mainly composed of oolite grains resulting from the activities of unicellular algæ, are forming on the shores of Great Salt Lake in Utah.

The Junagarh limestone overlying the Deccan basalt, in the Kathiawar Peninsula of Western India, is a typical example of this kind of rock. It underlies the city of Junagarh, situated 30 miles from the sea; and in places is over 200 feet in thickness. It is mainly composed of particles of shallow-water calcareous organisms, most of which are living forms. Each particle is surrounded by a coating of secondary carbonate of lime, and the whole mass is cemented into a compact rock by a later cement of carbonate of lime. Grains of mineral matter derived from the neighbouring igneous rocks constitute from 6·5 to 12·5 per cent. of the whole. Along the sea-borders it is usually mixed with siliceous sand.[1] In other places it is earthy and rubbly.

The limestone is divided by horizontal planes into tiers from 3 to 4 feet thick, these planes marking decided breaks in deposition. Evans[2] believed that at the time of formation the peninsula stood 150 feet lower than at present, and had the character of an island or group of islands. If one may judge from the limited distribution of wind-borne coral muds and silts in the Pacific islands, it is improbable that the Junagarh deposits were carried 30 miles inland.

Carbonaceous Limestone.—A limestone containing a considerable proportion of carbonaceous matter of vegetable or animal origin is called a *Carbonaceous* or *Bituminous Limestone.* Such rocks often give off a fetid smell when struck with a hammer, or when two pieces are rubbed together, and are, therefore, spoken of as *Stinkstone.*

Oolitic Structure.—Many of the Mesozoic limestones possess an oolitic structure; that is, they are made up of minute rounded grains about the size of a small pin-head, cemented together so closely that the rock presents the appearance of fish-roe; hence the name *oolite*[3] or *roe-stone.*

The origin of this peculiar structure is still uncertain. The grains consist of calcite possessing a radial and concentric structure. In many cases a grain of sand or a fragment of shell appears to have formed the nucleus around which the calcite formed. The carbonate of lime may have been deposited from solution on the floating earthy nuclei, just as moisture in a saturated atmosphere will collect on particles of dust.

The oolitic limestones furnish valuable building stones in almost every quarter of the globe. The *Ham Hill Stone* of Somerset; the *Portland Stone* of Dorsetshire, used in the erection of St Paul's Cathedral, London; the *Caen Stone* of Normandy; the *Swabian Stone* of Württemberg; the *Boticino Stone* of North Italy; the *White Stone* of Kentucky—are some well-known examples.

The oolitic ironstones of Cleveland and Northampton, in which the grains consist of carbonate and oxide of iron, have been shown to result from the alteration of ordinary oolitic limestone.

Cone-in-Cone Structure.—Concretions of limestone in Cretaceous formations are frequently covered with an outer layer of limestone usually from two to four inches thick, composed of a mass of radial, fibrous, funnel-shaped, crystalline forms that fit into each other, producing a *cone-in-cone* structure. The origin of this structure is not yet understood.

Dolomitic Limestones.—Practically nearly all limestones contain a small amount of magnesium carbonate, as a rule less than 2 per cent. Calcium carbonate is a less stable

[1] F. Fedden, *Mem. Geol. Surv. India*, vol. xxi., 1885, pp. 126–128.

[2] J. W. Evans, "Mechanically Formed Limestones from Junagarh (Kathiawar) and other Localities," *Quart. Jour. Geol. Soc.*, vol. lvi., pp. 559–583.

[3] Gr. *oon*=egg, and *lithos*=stone.

compound than magnesium carbonate, and in many limestones the magnesium mineral replaces the calcium mineral, forming what is called a magnesium limestone or dolomite-rock.

Dolomite-rock may perhaps be produced directly, as an original formation, by the evaporation of aqueous solutions charged with carbonates of calcium and magnesium; but it is generally recognised that most dolomite limestones and dolomite-rocks were at first ordinary limestones, composed mainly of calcium carbonates, and a small proportion of magnesia, and an even smaller amount of soda, potash, and other impurities.

The replacement of lime by magnesia is called *dolomitisation*, and it has taken place, to a greater or less extent, in all calcareous rocks, both old and young. The bore-holes at Funafuti provided instructive evidence of the dolomitisation of coral-rock of probably late Tertiary age; and many raised coral reefs in the Pacific islands show a mineralogical change of the same kind. The stony part of corals is composed of aragonite, a calcium mineral that is less stable than calcite, and hence more liable to chemical dissociation and replacement.

Sea-water is relatively rich in magnesium sulphate and it is generally believed that there is an interchange between calcium carbonate and the magnesium salt, resulting in the formation of dolomite and calcium sulphate. The common association of the mineral gypsum (calcium sulphate) and beds of dolomite-rock appears to support this view. On the other hand, it has been shown by analyses that a small amount of magnesium carbonate is extracted from sea-water by many of the marine organisms that build calcareous skeletons. Shells and corals contain magnesium carbonate in amount from 0·15 to 7·64 per cent., 1 per cent. being above the average. Crinoids[1] contain $MgCO_3$ in proportions ranging from 7·28 to 12·69 per cent. The calcareous alga *Lithothamnium* that plays an important part in the structure of most modern coral reefs contains from 1·95 to 13·19 per cent. of $MgCO_3$.

From these analyses it follows that all limestones formed by marine organisms must contain magnesium carbonate. Further, it would appear that $MgCO_3$ has a tendency to accumulate while the more soluble $CaCO_3$ is dissolved and carried away. That is, by the leaching of the calcium carbonate and concentration of the magnesium carbonate the rock becomes enriched in magnesia, till the true dolomite ratio, 45·27 per cent., is reached. The concentration may be effected by sea-water or percolating rain-water.

A striking illustration of the dolomitisation of coral-rock is provided by the borings at the atoll of Funafuti.[2]

Magnesium Carbonate in Coral-rock, Funafuti.

Depth. Feet.	Per Cent. $MgCO_3$.	Depth. Feet.	Per Cent. $MgCO_3$.
4	4·23	295	3·6
13	7·62	400	3·1
15	16·40	500	2·7
20	11·99	598	1·06
26	16·00	640	26·33
55	5·85	698	40·04
110	2·11	795	38·92
159	0·79	898	39·99
200	2·70	1000	40·56
[illegible]	4·90	1114	41·05

Borings at Key West, Florida,[3] show a progressive magnesium enrichment from 0·29 per cent. of MgO at a depth of 25 feet to 6·70 per cent. of MgO at 755 feet. Thereafter there was a falling off, with various fluctuations down to 2000 feet, where the percentage of MgO was 1·06.

It has been proved by experiments that high temperature and a pressure of from one to five atmospheres favour the interchange of $MgCO_3$ and $CaCO_3$; and these conditions always prevail in warm tropical seas down to a depth of 32·5 fathoms where dolomitisation has been shown to be most active.

[1] F. W. Clarke, *The Data of Geochemistry*, U.S. Geol. Survey, Washington, 3rd ed., 1916, p. 565.
[2] *The Atoll of Funafuti*, Royal Society, London, 1904, pp. 362–389.
[3] *The Data of Geochemistry*, U.S. Geol. Survey, 3rd ed., 1916, p. 569.

CHEMICAL PRECIPITATION OF LIMESTONES.

The prevalence of massive beds of apparently unfossiliferous limestone in the pre-Cambrian and Cambrian systems of North America has induced Professor R. A. Daly [1] to revive the chemical precipitation hypothesis. He postulates that the pre-Cambrian land areas were mainly composed of silicates. As only a small amount of lime entered the sea, the marine animals would be mostly soft-bodied, and since the higher scavenger types were not yet evolved, the sea-floor would be strewn with putrefying animal bodies. In course of time the ammonium carbonate resulting from the animal putrefaction would convert the chloride and sulphate of calcium into the carbonate of calcium, which would be precipitated in the form of limestone. It may be objected to this view that if the sea contained calcium carbonate in sufficient amount to form massive beds of limestone by precipitation, this amount should have been sufficient to provide the skeletons of lime-secreting organisms.

Calcareous algæ have been important limestone-builders since the Cambrian, and many so-called coral reefs of to-day might consistently be called Nullipore reefs. The calcareous framework secreted by algæ is minute, fragile, and usually crystalline, even in the living tissues; hence easily comminuted and subject to alteration and complete obliteration of the original structure. Conceivably calcareous algæ may after all be responsible for the formation of these apparently unfossiliferous Palæozoic limestones.

Rock-phosphates.—All rocks and soils and all natural waters contain a small amount of phosphoric acid, a substance which plays an important part in the economy of all plant and animal life. The ultimate source of phosphoric acid may be traced back to the mineral apatite, which is a common primary constituent of igneous rocks of all kinds and of all ages. Secondary apatite, formed by the dissolution and subsequent concentration of pre-existing phosphatic substances, also occurs as veins and massive segregations in gneiss, mica-schist, and other crystalline (metamorphic) rocks. It is sometimes found in ordinary limestone, sandstones, and shales of Silurian, Carboniferous, Jurassic, and Cretaceous and Tertiary formation. It has even been observed as the petrifying material of fossil wood.

Apatite occurs in crystalline forms; also as massive, fibrous, and earthy aggregates. It is phosphate of calcium, with fluoride or chloride of calcium, or both. As a rule, the calcium phosphate ranges from 91 to 93 per cent., the calcium fluoride from 4 to 8 per cent., and the calcium chloride from a trace to 4 per cent.

Phosphoric acid and fluorine are essential requirements of nearly all forms of animal life. The higher orders obtain their supply through the agency of plants, while marine organisms derive their supply from sea-water.

In weathered or decomposed rocks apatite as a crystalline mineral is dissolved, and reappears in the form of earthy and massive phosphates deposited from percolating waters.

All natural waters contain dissolved phosphates, which thus find their way into soils, whence they pass into plants and eventually into the bones and tissues of animals. The bodies of animals are rich in phosphates, and hence on death these become an important source of phosphoric acid. The excreta of animals also contains phosphates in an easily soluble form. Thus from the inorganic mineral phosphate to the decaying animal remains we get a cycle of complex chemical and physiological processes.

Most ordinary limestones contain a small amount of calcium phosphate, and in certain conditions, as the chemical corrosion of the calcareous rock by the percolation of surface waters proceeds, the phosphoric acid may be concentrated and redeposited in the form of valuable aggregates of massive calcium phosphate that are usually called rock-phosphate. This form of concentration often takes place in limestones associated with beds of glauconitic sands. Rock-phosphates of this type commonly occur in Cretaceous and older Tertiary formations. Those in Florida, Algeria, Tunis, and New Zealand are of great value for the manufacture of manures.

In the tropical seas, fish-eating birds often congregate in countless myriads on low, flat-topped coral islands. In the course of many years the surface of these islands may become piled up to a depth of many feet with bird-guano, which is a valuable plant fertiliser.

Below the layer of guano there often occurs an irregular layer of solid rock-phosphate (calcium phosphate). Guano is rich in soluble phosphate, existing in the form of ammonium phosphate, which is carried down into the porous coral rock lying below. The phosphoric acid displaces the carbonic acid and forms massive aggregates of calcium phosphate which remain behind after the guano has disappeared. The valuable phosphate deposits on Nauru, Ocean, Makatea, and Walpole Islands in the South Pacific were formed in this way.

Silicification of Limestones.—Calcium carbonate and silica under certain conditions are mutually able to replace one another, such replacements being common in rock-masses and in ore veins. Most usually the calcium carbonate is replaced by silica molecule by molecule,

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[1] R. A. Daly, "The Limeless Ocean of pre-Cambrian Time," *Amer. Jour. Sci.*, 1907, pp. 93–115.

producing the rocks known as chert and flint. When calcareous organisms are replaced by silica, the original structures may be perfectly reproduced.

As a rule the silica already exists in the limestone in the form of sponge spicules. These are composed of colloidal silica, which is readily soluble in alkaline waters percolating through the rock. The dissolved silica is often deposited again in the solid form around some siliceous nucleus, forming a nodule or sometimes a bed of flint (chalcedony). Silica in its alkaline aqueous solution is attracted to points of more than average concentration, hence any siliceous nodule or organism will act as a nucleus for deposition. The beds of chert associated with Palæozoic and younger limestones were formed by the secondary concentration of sponge remains. It is also probable that the massive beds of *flint* or *chert* intercalated with the older Tertiary strata of New Zealand were formed by a similar process of replacement.

Siliceous Rocks.

Chert and Flint.—Many of the older limestones are intercalated with sheets or lens-shaped masses of siliceous rock called *Chert*, which is mainly composed of the tiny siliceous shells of *Radiolaria*, the siliceous cases of *Diatoms* (diminutive aquatic plants of a low type), and the spicules of sponges. The silica is carried in solution in sea-water, and these organisms are able to extract it for the building of their coverings or skeletons.

Chert is usually a fine-grained buff-grey, dark-grey, red, brown, or black rock. It is brittle, and breaks with a conchoidal fracture. The siliceous organisms of which it is composed are set in a cement of secondary silica deposited by infiltration.

Lydian stone is an intensely hard, brittle, fine-grained black chert used as touchstone.

Beds, lenticular tabular masses, and nodules of *Flint*, which is a form of chert, frequently occur in chalk and other earthy limestones. The nodules are usually arranged in layers parallel with the bedding planes. Like chert, flint is composed of silica extracted from sea-water by radiolarians, sponges, and diatoms, or deposited by chemical action.

The soft incoherent forms of diatomaceous earth are called *Infusorial Earth* or *Tripoli*. They are commercially valuable as the base or matrix of many nitro-glycerine compounds, the tiny siliceous shells possessing great absorbent properties.

Carbonaceous Rocks.

These rocks include the different varieties of coal and graphite.

Coal is altered vegetable matter. It consists essentially of carbon combined with oxygen, hydrogen, nitrogen, and a certain amount of earthy matter which is left as a residue, or ash, when the coal is burnt.

The progressive changes that take place in the formation of coal are seen in the different varieties of that mineral, ranging from peat to anthracite.

Wood.

Peat.—Consisting of decomposing vegetable matter.

Lignite.—Compressed and altered peat showing woody structure.

Brown Coal.—Altered lignite showing no woody structure.

Bituminous Coal.—Cokes or cakes when burnt.

Anthracite.—Consists mainly of carbon.

The process of alteration consists mainly in deoxidation and dehydration. In wood the average percentage[1] of oxygen is 43·20, in peat 35·56, in lignite 20·50, in bituminous coal 8·69, and in anthracite 2·72.

[1] F. W. Clarke, *The Data of Geochemistry*, Bull. 616, U.S. Geol. Survey, Washington, 3rd ed., p. 755.

Peat consists of stems, roots, leaves, and mossy vegetation, and may be seen in process of formation at the present day on the sites of ancient forests, and on moss and heath-covered water-logged lands. In recently formed peats, the vegetable matter is only slightly altered; while in the older peats, it is partially carbonised owing to the escape of some of the oxygen and hydrogen.

Lignite [1] is a peaty accumulation originating chiefly from the wood of conifers that has become covered with sediments. It represents the second stage in the formation of coal; and although the woody structure of the vegetation is still well preserved, there has been a considerable elimination of water and gaseous products.

Brown Coal is the next phase. It represents a greater degree of alteration than lignite. Some of poorer qualities cannot be distinguished from lignite, while many of the better grades approach a true coal.

Bituminous Coal represents a still higher degree of alteration, and in it all trace of the original woody structure has generally been obliterated. Microscopic examination, however, shows that many coals are composed of the spores of plants allied to ferns, club-mosses, and horse-tails. Others consist mainly of woody fibre and bark.

Anthracite [2] is the hardest coal. It consists almost entirely of carbon, practically all the gaseous products having been eliminated.

The anthracites of Wales and Pennsylvania are Carboniferous; and the semi-anthracites of New Zealand, Eocene. At Malvern, in the last-named State, the brown coal has been converted into anthracite by contact with a sheet of basalt.

Composition of Coal.—The constitution of coal can be very well shown by a simple test—

(1) Weigh out 100 grains of finely powdered coal; place in a platinum dish and dry carefully at a temperature not exceeding 212° Fahr. The loss of weight=the water.

(2) Place the dish over a Bunsen burner with the lid of the dish tipped slightly to one side. Apply a dull red heat and burn off the volatile gases. The loss=volatile *hydrocarbons*, and the residue=*fixed-carbon* plus *ash*=*coke*.

(3) Remove lid; tip the dish slightly to one side and burn off the carbon, keeping the heat going till only a grey or reddish-grey ash remains. The residue=*ash*; and the ash subtracted from the weight obtained in (2) gives the *fixed-carbon*.

If a fine balance is available, 10 grains of coal will be sufficient for the test. Tabulating the results, we may get, for example—

Water,	2·00
Hydro-carbons,	34·00
Fixed-carbon,	62·50
Ash,	1·50
	100·00

Cannel is a dull earthy shaly variety of coal often possessing a conchoidal fracture. It contains a large amount of coal gas, and for that reason is valuable for gas-making. It sometimes contains shells and fossil fish, and may pass at its edges into bituminous shale. These facts would indicate that cannel is

[1] Lat. *lignum*=wood. [2] Gr. *anthrax*=carbon.

not formed of vegetation that grew in place, but is a sapropelite,[1] *i.e.* a deposit of rotten organic material on the floor of shallow water-basins.

Jet resembles cannel coal, but is harder and blacker, and takes a fine polish. It is found at Whitby in Yorkshire, and elsewhere. Its lightness renders it suitable for personal ornaments.

Conditions of Coal Formation.—Coal is the result of the growth of a dense jungle-like vegetation on low-lying swampy areas on the sea-board near the mouth of great rivers. The deltas of the Mississippi and the swampy forests of the Amazon and Orinoco probably approach the conditions in which the coal vegetation flourished.

Coal is usually found resting on an *under-clay*, which is the soil in which the vegetation grew. In the coals of Westphalia and Nova Scotia there have been found the remains of trees still standing in the position in which they grew, with their rootlets penetrating the under-clay. This evidence supports the contention that many coals now occupy the original sites on which the forests grew.

After centuries of growth, the accumulation of decaying vegetable matter became buried under a covering of sand when the coastal lands subsided and became submerged.

The existence of numerous seams of coal in the same formation separated by beds of sandy material would indicate a corresponding number of oscillations of the land, each elevation being marked with a revival of jungle or forest conditions.

The thickness of the strata between the different seams of coal affords some evidence of the duration of each subsidence; but the clay or stone-partings met with in many coal-seams cannot always be taken as an evidence of submergence. They may mark the encroachment of flood-waters on to the forest-lands during an abnormal inundation whereby a layer of mud was deposited among the vegetation, whose growth would be retarded but not destroyed.

Quality of Coals.—Coals enclosed in porous grits or sandstones are usually of inferior quality; while those interbedded with close-grained fire-clays and compact sandstones are nearly always high class. The Upper Cretaceous system at Kaitangata, New Zealand, contains two coal-bearing horizons, a lower and an upper. In the lower horizon, which consists of loose quartzose sands and porous conglomerates, the coal is an ordinary lignite; while in the upper horizon, in which the seams are enclosed in thick beds of compact sandstone conglomerate, the coal is a hard bright coal of superior quality.

The quality of the coal is not dependent on the age of the enclosing rock, but, to a certain degree, on the nature of the plants from which they originate.

Age of Coals.—Lignites are generally confined to the younger Tertiary formations. Brown coals are found in rocks ranging from the Cretaceous to the Pliocene; while true coals occur in all formations from the Cambrian to the Eocene.

The anthracite of County Cavan in Ireland is Silurian; the true coals and anthracites of Great Britain, Continental Europe, and Pennsylvania, Carboniferous; the coals of New South Wales, Carboniferous and Permo-Carboniferous; China and of Tasmania, Victoria, and South Australia, Jurassic; and the semi-anthracites and bituminous coals of New Zealand, Eocene.

The brown coals of South Hungary, Transylvania, and North Germany are Lower Miocene; of New Zealand, Upper Cretaceous and Lower Miocene: the lignites of Ireland are Pliocene.

[1] Gr. *sapros*=rotten, and *pelos*=mud.

All the greatest coal-deposits in the globe are of Carboniferous age, which would indicate that plant-life in this period reached a development and luxuriance unrivalled in any other geological age. The ferns, mosses, equisetums, lycopodiums, and lepidodendrons, which constitute the bulk of the Carboniferous coals, grew to a gigantic size, resembling in habit the forest trees of the present day.

Graphite.[1]—The ultimate phase of altered coal would appear to be represented by *graphite*, from which all the gases have been eliminated, only carbon and ash being left behind.

Lenticular beds of graphite, frequently associated with crystalline limestones, are found in Canada, Bavaria, Bohemia, New South Wales, interbedded with gneissic and schistose rocks of pre-Cambrian, Cambrian, and Silurian age. Graphite of fine quality is obtained from the Ordovician volcanic series at Borrowdale in Cumberland, and it is a constituent of graphite-slate, graphite-schist, and graphite-gneiss. Some of the Laurentian limestones of Canada are so charged with it as to be profitably mined for it.

Masses of graphite still adhering to the original sandstone are sometimes found among the detritus on the slopes of Mount Egmont, a volcano which has broken through the brown coal-measures of that part of New Zealand. This graphite has obviously arisen from the alteration of pieces of coal that became entangled or engulfed in the ascending floods of andesitic lava.

Graphite also occurs in veins and filling cavities, as well as in disseminated scales in granitic rocks in Ceylon, from which a large proportion of the world's supply is drawn. Scales of graphite have also been identified in basalt and diorite. Such graphite can hardly have had an organic origin.

Ferruginous Rocks.

The rocks included in this group are chiefly important for their great economic value as ores of iron. They are usually limestones in which the carbonate of lime has been partly or wholly replaced by carbonate of iron. The oolitic iron-ore of the district of Cleveland in Yorkshire is a good example of this class of replacement deposit.

Chemically-formed Rocks.

(*a*) Carbonates—Limestones.
(*b*) Sulphates—Gypsum.
(*c*) Chlorides—Rock-salt.
(*d*) Silica—Siliceous sinter.

The Carbonate, Sulphate, and Chloride deposits of this group are composed of granular or crystalline precipitates that frequently occur as lenticular sheets interbedded with sands, clays, and shales. They were deposited on the floor of saline lakes or of the sea as a result of the evaporation and consequent concentration of the dissolved salts carried into the basin by the drainage of the surrounding country.

The sediments of saline inland lakes seldom contain fossils except those carried into the basin by streams.

Carbonates.—Waters charged with the bicarbonate of lime or magnesia when they reach the open air part with carbonic acid, and the carbonates are at once deposited. *Travertine* or *Calcareous Sinter* is a soft spongy-looking carbonate of lime frequently deposited in rock-shelters and on hill-slopes in the form of rocky cascades where the calcareous waters issue at the surface.

[1] Gr. *grapho*=I write.

These waters are popularly called *petrifying springs*, from the circumstance that the carbonate of lime is frequently deposited on ferns, crosses, twigs, and leaves, the forms of which are thus preserved (fig. 116).

Many travertines become hard and crystalline in structure through the deposit of secondary calcite.

Dolomitic or magnesian limestones formed on the floor of saline lakes are not uncommon. The rock is often concretionary, granular, or finely crystalline in structure, and sometimes exhibits false-bedding. The precipitation of the mixed carbonates of lime and magnesia is partly due to the presence of sodium carbonate and partly to evaporation.

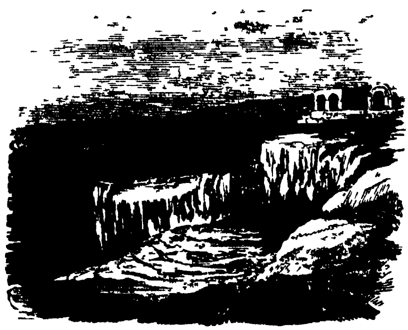

FIG. 116.—Deposit of travertine at a cascade.

Sulphates and Chlorides.—In inland lakes that have no outlet to the sea, situated in regions where the evaporation about balances the flow of the incoming streams, the water in the course of time becomes charged with soluble salts. When a certain degree of saturation is reached, a portion of the salts passes out of solution and is deposited on the floor of the lake. In this way sheets of gypsum and rock-salt have been formed on the floor of the Dead Sea and Great Salt Lake. The basins of many of the saline lagoons in Central Australia and Utah are covered with a thick crust of rock-salt mixed with various impurities.

Deposits of gypsum are sometimes formed in volcanic regions. A striking example may be seen at White Island, Auckland. Here the bed of the crater-lake is covered with a thick layer of gypsum deposited from the hot acid waters which fill the basin. The evaporation of the steaming water is rapid, but the loss is compensated by the mineral-laden waters that issue from the steam-holes and hot springs around the margin of the crater.

Rock-Salt Deposits.

The most important soluble salt occurring in stratified deposits is rock-salt, the sodic-chloride, NaCl. It is found in marine sedimentary rocks of nearly all ages, and must always be regarded as a residuum of evaporated sea-water. In 1000 parts of ocean-water there are 35 parts of dissolved matter, which has the following average composition :—

$NaCl$	78·32
KCl	1·69
$MgCl_2$	9·44
$MgSO_4$	6·40
$CaSO_4$	3·94
Other matter	0·21
	100·0

The formation of salt is only possible in a basin containing highly concentrated water, and therefore must have taken place in parts of the sea that were without an open connection with the great ocean. The enormous thickness

of many salt-deposits compels us to conclude that there was a continued supply of salt-water to the basin, which by a submarine bar was prevented from flowing back. Such a situation is observed now at the Karabugas, a bay of the Caspian Sea. A rather torrid climate will be necessary for the evaporation of enclosed or partially isolated ocean-basins. The salt of desert salt-lakes has rarely the composition of the great salt-deposits. Even in the Dead Sea, the water of which contains 19·26 per cent. of dissolved matter, the $MgCl_2$ surpasses the NaCl in quantity. Our large salt-deposits cannot have originated in salt-lakes.

Mode of Occurrence.—Rock-salt occurs either in colourless, clear masses or is rather spathose. It may be mixed with clay, iron, etc., by which it is coloured grey, red, or yellow. It often contains some $MgCl_2$. It is either stratified with alternating beds of anhydrite, gypsum or clay, or occurs as unstratified masses or lenticular bodies.

Together with the rock-salt there occur anhydrite and gypsum, which are the first to be deposited, and dolomite. Fossils are rarely found in these deposits (Wieliczka is an exception), probably for the reason that in the highly concentrated sea-water organic life could not exist.

Potassic Salt.—Only in rare cases has the evaporation of a sea-basin proceeded so far that the most soluble salts could be deposited above the rock-salt. These salts are called the potassic salts because of the high amount of potassic combinations in them, particularly carnallite ($KCl+MgCl_2+6H_2O$) and kainit ($KCl+MgSO_4+3H_2O$). These salts are used in the chemical industry and as fertilisers.

Important Salt-Deposits.—By far the majority of salt-deposits consists of rock-salt only. Those of the Indian Salt Range are of Tertiary age, but, by an overthrust, are overlain by the Cambrian. Those of France and many of England (Nottingham, Derby, Stafford, etc.) are Triassic. The celebrated deposits of Poland (Wieliczka, etc.) occur in the foot-hills of the Carpathian Mountains and are of Miocene age. The salt here forms beds of a thickness up to 65 feet and is interbedded with clay, anhydrite, and sandstone.

Potassic salts are found almost only in the northern part of Germany, where they, together with gypsum and rock-salt deposits, belong to the Upper Permian, the so-called Zechstein. The most celebrated mine is that of Stassfurt in Prussia. Here, as in several other places, one finds two series of salts, of which the lower one is topped by the potassic salts.

There are different types of salt-deposits. While in part the strata are horizontal, in others the salt forms columns of considerable diameter, which pierce through the younger sediments. The astonishing thickness of these salt-masses—the deep-boring of Sperenberg, near Berlin, has met one of more than 3500 feet—is due to this ascending of the salt, produced by the weight of the overlying strata upon the plastic salt.

The most important minerals of the potassic salts are: Sylvin, Carnallite, Polyhalit, and Kieserit, which are sulphates and chlorides of potassium, Magnesium, and Calcium.

Up to the war Germany was the only country that possessed potassic salts in large quantities, but now the Oligocene potassic salts of the Alsace have come into the hands of France.

Water which touches salt-deposits dissolves them and forms, if it comes to the surface, salt-springs. By boring, artesian salt-springs are made and salt thus obtained without mining.

Some of the potash (carnallite) beds associated with the rock-salt deposits near Stassfurt are bent and distorted, while the rock-salt beds are undis-

turbed. The associated sandstones and shales are often undisturbed; hence the forces which have brought about this peculiar deformation are evidently of a local character and not tectonic.

In homogeneous rocks of fine texture, recrystallisation may exert a powerful deforming effect along the original structure lines, and may even deform the enclosing rocks. It is probable that the *salt-domes* of Louisiana, eastern Texas, and of North Germany, especially in Hanover and Brunswick, of Transylvania, Pyrenees and Southern Algeria, and the tilting of the associated strata may have originated as a result of the molecular pressure of recrystallisation.

The salt-domes are elliptical in section, with folded and often much distorted layers of salt, gypsum, or potash which rise through the enclosing strata, deforming them, and presenting a plug-like relationship to them. Though tectonic folding has undoubtedly occurred in places, it is generally believed[1] that the deformation is the result of internal or *endogenetic*[2] pressure.

Silica.—In regions of expiring volcanic activity, the thermal waters

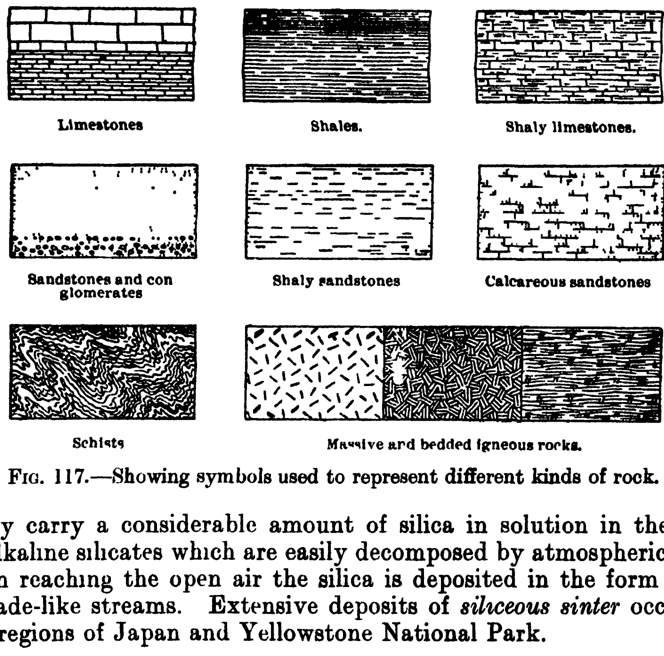

FIG. 117.—Showing symbols used to represent different kinds of rock.

frequently carry a considerable amount of silica in solution in the form of soluble alkaline silicates which are easily decomposed by atmospheric carbonic acid. On reaching the open air the silica is deposited in the form of sheets and cascade-like streams. Extensive deposits of *siliceous sinter* occur in the volcanic regions of Japan and Yellowstone National Park.

CONVENTIONAL SYMBOLS.

The symbols used by geologists to represent the more common rocks on maps are shown in fig. 117.

SUMMARY.

(1) Sedimentary rocks, according to the character of the constituents, may be classified as *Detrital*, *Organic*, or *Chemical*.

(2) *Detrital* rocks are composed of sediments of various degrees of texture derived from the denudation of pre-existing rock-masses.

[1] F. F. Hahn, "The Form of Salt Deposits," *Economic Geology*, vol. vii., 1912, pp. 120–135.
[2] Gr. *endos*=within, and *genesis*=production.

In *breccia* the material is angular ; in *conglomerate*, water-worn and pebbly ; in *sandstone*, sandy ; and in *clays*, *shales*, and *slates*, very fine or clayey.

The cementing medium may be carbonate of lime, silica, oxide of iron, or a paste of sand and clay. The colour is usually determined by the degree of oxidation and hydration of the iron which is nearly always present.

(3) *Organic* rocks may be composed of animal or plant remains. They may be divided into four groups according to their composition, viz. *Calcareous*, *Siliceous*, *Carbonaceous*, and *Ferruginous*.

The *Calcareous* division comprises the limestones that consist of the calcareous shells and organisms of molluscs, corals, crinoids, and foraminifera. Some limestones, like chalk, are soft and earthy ; others hard and massive, like the Belgian limestones ; while many possess a granular or finely crystalline structure. Coralline limestones may develop a crystalline structure through the infiltration of calcareous waters ; and by the replacement of a portion of the carbonate of lime with magnesium carbonate, the rock may be *dolomitised* or altered into a magnesian limestone or dolomite that may resemble the older dolomitic limestones.

Limestones may contain certain impurities. They may be clayey, forming an *argillaceous limestone* from which hydraulic cement is made, sandy, pebbly, or siliceous.

The *Siliceous* rocks of this group are *chert* and *flint*, mainly composed of *radiolarians* and of *diatoms*—tiny aquatic animals and plants that possess the power of extracting silica from sea-water.

The *Carbonaceous* rocks include all the known varieties of coal ranging from peat to anthracite.

The *Ferruginous* rocks are mostly carbonate of iron that has replaced the carbonate of lime in oolitic limestones.

(4) *Chemically formed* rocks comprise carbonates, sulphates, chlorides, and silica. The last is deposited by hot springs in volcanic regions in the expiring or solfataric stage of activity ; the others are deposited as precipitates on the beds of inland saline lakes. When the evaporation balances the inflow, the mineral matter carried into the lake in solution in time reaches a point of saturation, when precipitation takes place. In this way beds of *gypsum* and *rock-salt* have been deposited on the floor of the Dead Sea and Great Salt Lake.

CHAPTER XV.

VOLCANOES.

Definition of Volcano.—A volcano may be defined as a spot where magma or magmatic products are brought to the surface. In a restricted sense, a volcano is a more or less conical elevation, which may have a crater at its summit, from which steam, gases, streams of lava and showers of dust, and scoriæ are ejected.

Volcanoes classified.—Regarding their activity volcanoes may be classified as—

(*a*) **Extinct.**
(*b*) **Dormant.**
(*c*) **Active.**

An **Extinct** volcano is one that is not known to have been active within historic or traditional times.

A **Dormant** volcano is one that enjoys intervals of complete quiescence between the different eruptions, which may be separated by hundreds or even thousands of years.

Active volcanoes are always in a state of disturbance. Their paroxysmal outbursts are, however, usually intermittent and may be separated by long intervals of comparative quietude, during which the only evidences of activity are the emission of steam, and minor explosions that may give rise occasionally to showers of dust and *lapilli*.[1]

Examples:—

Extinct volcanoes,	. The craters of Auvergne in France, and Eifel in Rhenish Prussia.
Dormant volcanoes,	. Ruapehu and Tarawera, New Zealand.
Active volcanoes,	. Etna, Stromboli, Vesuvius, Hekla, Cotopaxi, Kilauea, Ngauruhoe.

This classification is not altogether satisfactory. Historic time is so short relatively to the life of a volcano that the so-called extinct cone of to-day may be the active volcano of to-morrow. Up to the time of its first known eruption in 97 A.D., Vesuvius was looked upon as extinct. Similarly Tarawera, which burst into activity with such startling suddenness in 1886, was never known to have shown the least sign of action before that date. It had suffered considerably from denudation and possessed no visible crater. The whole aspect of the mountain seemed to indicate a state of complete extinction of long duration.

Sites of Volcanoes.—The vent of a volcano may break through any geological formation, and may originate on the sea-floor, on dry land near the sea, on a plateau, or mountain-chain. The numerous volcanic cones of Auckland are

[1] Ital. *lapilli*=little stones (mostly from the size of a pea to that of a small walnut).

piled up on a platform of Tertiary marine sandstones and clays not much above sea-level; the Miocene volcanoes of Aüvergne burst through the granitic and gneissic plateau of Central France.

Types of Volcanic Eruptions.—Three types of volcanic eruptions may be distinguished—

(1) Crater eruptions =Vesuvian type.
(2) Fissure eruptions =Icelandic type.
(3) Explosive eruptions=Krakatoan type.

Vesuvian Type.—*Crater* eruptions are those in which the volcanic material is ejected from one central crater or from satellite vents connected with the main vent, as at Vesuvius, Cotopaxi, and Egmont.

Icelandic Type.—In *Fissure* eruptions there is a quiet welling-up of lava along a line of fissure, accompanied with little explosive action and hence expelling little or no ash or fragmentary matter. The great volcanoes Kilauea and Mauna Loa in the Sandwich Islands are fine examples of the fissure type of volcanic action. The lava floods of Idaho, Victoria, Oregon, Washington, and California form plateaux over 200,000 square miles in extent; and great basaltic plateaux also occur in Victoria, in Australia, and the Deccan in India. All have been formed by vast floods of lava that issued from fissure-rents of great length.

The greatest outpouring of lava in historic times took place in Iceland in 1783. Floods of lava issued from a fissure twelve miles long and poured over the land, diverting streams from their course, filling up river-gorges, and forming lakes of molten rock on the neighbouring plains. The main streams travelled over forty miles from the point of emission.

Hekla does not form a cone, but an oblong ridge which has been split by a fissure along its whole length that bears a row of craters.

Krakatoan Type.—These take place through the sudden expansive force of subterranean steam. They usually happen with appalling suddenness; and frequently their explosive force is so titanic that they rend and shatter the rocks at the point where the explosion is concentrated into fragments, which may be hurled far and wide with devastating effect. In a few hours forests may be destroyed, towns overwhelmed, lakes dried up, old landmarks obliterated, and the surrounding country converted into a lifeless desert.

The five most stupendous and destructive explosive eruptions of historic times are those of Vesuvius in 79 A.D., Krakatoa in 1883, Tarawera in 1886, St. Vincent in 1902, and Mount Kloet, in Java, in 1919.

Before 79 A.D., there was no tradition or record of former volcanic activity at Vesuvius. The ancient crater was overgrown with wild vines, while the mountain slopes and neighbouring plains were dotted with villages surrounded with vineyards and well-cultivated fields. At the base of the mountain stood the populous and cultured cities of Herculaneum and Pompeii.

The premonitory evidence of coming disturbance began with a series of earthquakes in 63 A.D., which caused much damage to buildings and created considerable alarm among the people living in the neighbourhood of the mountain. The earthquakes increased in frequency and violence, and in 79 A.D. finally culminated in a series of terrific explosions that truncated the bulk of the ancient cone by nearly one half, forming the well-known Monte Somma ring from which the present cone rises (fig. 118). The immense volumes of steam that issued from the crater were condensed and fell in torrential rains that swept down the mountain slopes carrying before them ejected dust and scoriæ. The floods of mud thus formed, together with the showers of falling

ejecta, buried the cities of Herculaneum and Pompeii and devastated the surrounding country.

The history of Vesuvius, till the eruption of 1036, was a long series of explosive outbursts, producing only fragmentary material. In that year there was an overflow of lava for the first time ; and from then onward the mountain entered on a new phase of volcanic activity.

Perhaps the most stupendous explosive eruption in historic times was that which took place at Krakatoa, a volcanic island in the Straits of Sunda, between Java and Sumatra, in August 1883, when a large portion of the island was destroyed and the remainder devastated with a thick covering of dust and other fragmentary ejectamenta. The sound of the explosions was heard at Ceylon, more than 2000 miles away ; and much of the dust was projected so high into the air and was so excessively fine that it was caught up in the upper currents of the atmosphere and carried many times round the globe, giving rise to a series of gorgeously coloured sunsets that continued for several months.

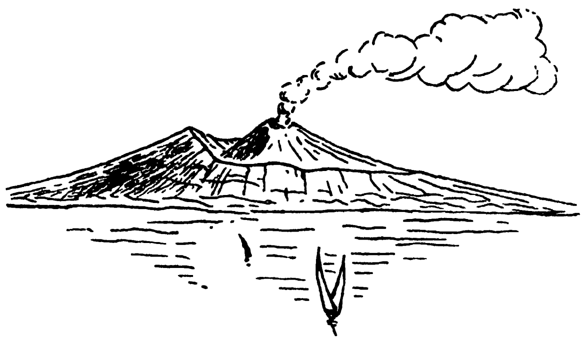

FIG. 118.—Vesuvius, showing the older crater-ring of Monte Somma and the new cone within it. (After Phillips.)

Particles of Krakatoan dust fell in Japan and America, and some even reached as far as Europe.

The disturbance in the surrounding sea was relatively greater than on land. The waves propagated by the explosions caused enormous loss of life on the adjacent coasts and low-lying islands. They travelled as far as Cape Horn, 7818 miles away.

The Tarawera eruption in New Zealand took place in June 1886, and was preceded by little or no warning. In a few hours after the first terrific outburst, the mountain and plateau at its base were rent with a gaping fissure nearly nine miles long. The volcanic energy soon became concentrated in numerous independent centres of explosive activity along the fissure, from which there issued continuous showers of fragmentary matter and enormous volumes of steam. The dust was spread over 10,000 square miles, overwhelming the neighbouring forests and native villages, and converting the country into a weird grey wilderness. Immense volumes of steam were condensed into rain which, uniting with the falling dust, formed a plastic mud that broke down the forest-trees and buried the hapless villages lying in the track of the powerful winds that accompanied the eruption.

The sounds of the explosions were heard at Christchurch, over 400 miles away. They resembled the detonations of cannon or violent blows on the side of an empty iron-tank. It was during this eruption that the far-famed Pink and White Terraces at Rotomahana were destroyed.

The disastrous explosive eruption of Montagne Pelée in Martinique is still fresh in the memory of everyone. In April 1902, the volcano began to emit steam, ashes, and sulphurous vapours. The latter were so abundant that horses dropped dead in the streets of St. Pierre, situated on the plain bordering the mountain. On 5th May, floods of mud descended from the crater where it had been accumulating for some time, and earthquakes were numerous. On 8th May, the eruption reached its climax. On that day a black cloud of dust, steam, and sulphurous vapours swept down through the breach in the crater fronting St. Pierre, passed over the plain, and in two minutes struck the city, which was at once overwhelmed, and the inhabitants to the number of 30,000 were killed. The detonations of the explosions that followed were heard 300 miles away.

The great crater of Montagne Pelée is now occupied by a fragmental cone that terminated in a column of solid lava several hundred feet high. This

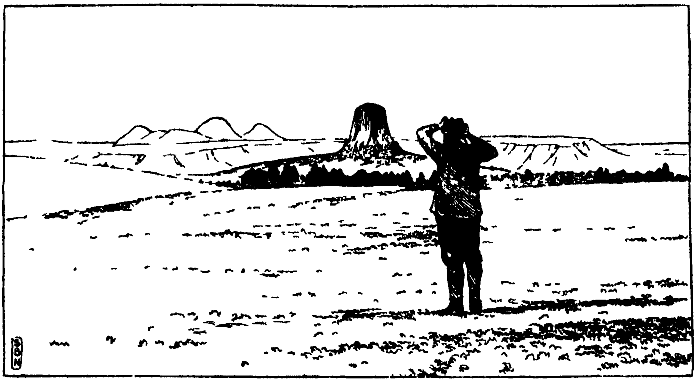

FIG. 119.—Showing plug of phonolite lava, Mato Teepee, Missouri, *U.S. Geol. Surv.* (After Jagger.)

column is believed to be the plug of lava that solidified in the vent and was pushed up by the expansive force of the steam and vapour below soon after the eruption.

The eruption of Mount Kloet, in Java, in 1919, was even more destructive than that of Montagne Pelée. In June of that year a cold-water lake near the summit was suddenly emptied into the crater, and almost at once a terrific explosion took place. The side of the mountain was blown out, and floods of molten lava flowed with incredible speed over the surrounding country. Explosion followed explosion, and filled the air with a cloud of ash and fine dust, so dense that the day became as dark as night. After a few hours the explosions died down, but the streams of lava pursued their onward course. Scores of native villages were obliterated, but the greatest destruction of life took place at Blitar, situated about 30 miles from Mount Kloet. Two streams of lava encompassed the town and trapped the inhabitants, all of whom perished without hope of escape.

The lava streams and ash devastated over 2000 square miles of country, and killed about 50,000 natives and 100 Europeans.

Craters.—The crater [1] of a volcano is a cup-shaped depression at the summit which communicates below with a fissure in the Earth's crust. It is through this vent or pipe that the ejecta and gases issue from below.

[1] Gr. *krater*=a large bowl.

Active and dormant volcanoes as a rule possess well-defined craters. In extinct volcanoes, older than Pliocene, the craters and vents are generally obliterated by denudation; but scores of craters in the Auvergne and New Zealand, that probably date back to the Pliocene, are still well-preserved.

Volcanic Cones.—The fragmentary material and lava streams ejected by volcanoes accumulate around the neighbourhood of the vent, and thus build up the cone-shaped elevations that are so characteristic of volcanoes. At

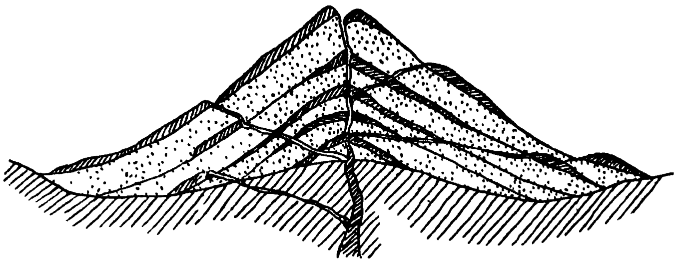

Fig. 120.—Showing structure of volcanic cone composed of lava streams and beds of ash.

Auckland, where some of the cones have been cut down for the extraction of building-stone, the different layers of material are seen to dip away from the central vent in all directions, as shown in fig. 120.

Tuff-Cones.—These are volcanic cones composed of dust and scoriæ piled up by one or more eruptions. Frequently the material is spread out in distinct layers that may in some cases present the appearance of well-stratified aqueous strata. This arises from the fine and coarse material being arranged in alter-

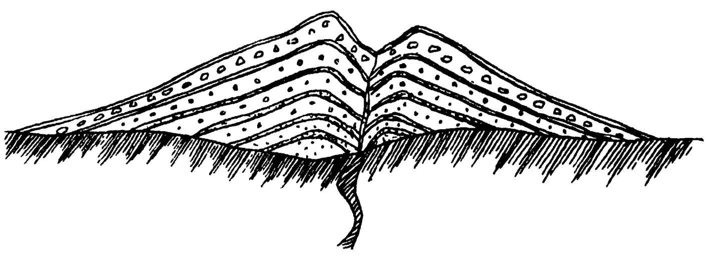

Fig. 121.—Showing structure of a tuff-cone with alternations of fine and coarse ash.

nating layers. The sorting was apparently effected by the varying force of the explosions and the winnowing action of the wind.

The structure of a tuff- or cinder-cone is shown in fig. 121.

Lateral Cones.—In some of the larger volcanoes, the eruptions of lava do not always take place from the central crater at the summit, but from smaller vents on the sides. The uprising lava in the central fissure exerts enormous pressure on its walls; and in the case of a high volcano, rupture may take place at some weak point before the lava has risen high enough to overflow the crater-lip.

The fluid pressure of a column of molten rock with a specific gravity of 2·65 is 114·75 lbs. per square inch for every hundred feet of height, or 72 tons per square foot for every thousand feet. When the crater-walls are unable to withstand this pressure, rupture takes place at the weakest point.

The summit-crater of Etna is nearly always in a state of mild activity, emitting clouds of steam and dust, but the eruptions of lava usually take place from lateral vents around which there have been built small *parasitic cones*, ranging from 200 to 600 feet high.

Lava Streams.—When a stream of lava issues from a vent, it glows with a

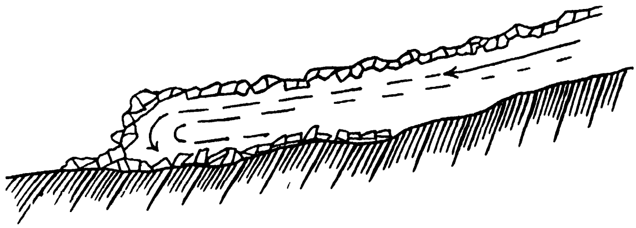

FIG. 122.—Showing mode of progression of lava stream.

white heat, and at night may light up the sky overhead with a ruddy glow, as of a forest fire. It flows with the motion common to all viscous fluids, its rate of flow depending on the fluidity and depth of the mass, the steepness of the declivity, and the roughness of the ground over which it descends.

The upper surface, as it cools, assumes a red heat, and finally becomes

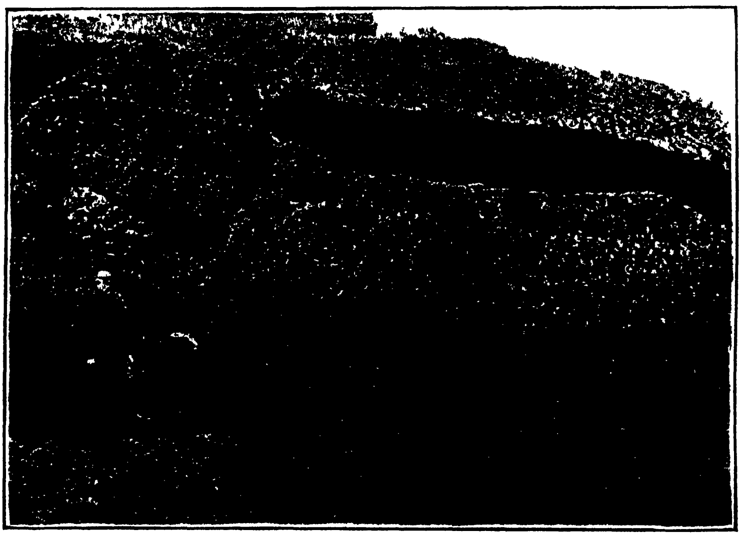

FIG. 123.—Showing corded structure of lava, Galtalaekr, Hekla, Iceland. (After Tempest Anderson.)

black and cindery, the last effect being due to the escaping steam and gases which are expelled during the process of cooling.

The onward motion of the fluid mass below breaks up the solid surface into jagged, cindery, ragged cakes that are tilted up and frequently half-engulfed in the molten flood below. Moreover, the rolling motion of the stream tends to pile the solid jagged masses into irregular mounds that are slowly carried forward on the moving tide of lava.

The front of the lava stream progresses by a rolling motion, by which the upper surface becomes the lower. In this way, before the stream has travelled far, the bottom has become a confused tangle of angular blocks that are slowly dragged along by the pasty mass (fig. 122).

The upper surface of very fluid lavas frequently becomes spongy and scoriaceous, while the slowly cooling mass below assumes the curious ropy and streaky appearance of boiled sugar that has been poured down an inclined plane. The plane of this *flow-structure* is always parallel to the surface over which the lava travels, but accidental obstructions may cause the fluxion-planes to become bent, twisted, or gnarled.

In many volcanoes the lava rises up and fills the crater, over the rim of which it flows in a gentle stream; but when any portion of the crater-wall is weak, it may be carried away. The craters of Stromboli, Vesuvius, Ruapehu, White Island (Plate XVI.), and many other volcanoes have been breached in this way.

The molten lava, as it pours out of the vents, resembles the slag of a blast-furnace. When it cools rapidly, as it frequently does, at the thin edges of the

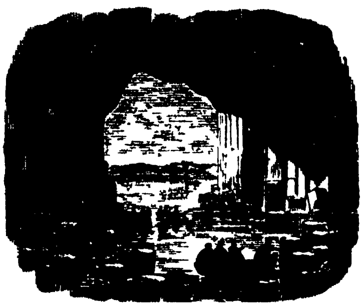

FIG. 124.—Fingal's Cave, Staffa, eroded by the sea in basalt of columnar structure.

stream, or where it flows into a sheet of water, it sometimes solidifies in the form of a glass.

The vitreous or glassy form of acid lavas is called *obsidian* or simply *volcanic glass*; and the black, glassy form of basic lavas, *tachylite*. *Pumice* is the light, frothy, fibrous, spongy glass which forms on the surface of acid lavas. In other words, it is the cindery form of obsidian, and is frequently composed of a matted mass of glassy fibres.

Columnar Structure.—This structure is frequently seen in effusive rocks. It is developed by the stresses that arise in a thick stream of lava as it passes from the liquid to the solid state. As the result of the cooling and shrinking, the crust of the lava becomes intersected with more or less symmetrical sets of cracks that divide the surface into hexagons that fit one another like the cells of honey-comb. As the pasty mass under the crust cools, the cracks extend downwards at right angles to the surface. The columns are arranged in a radial or fan-shaped form, where the basalt has cooled within a crater-shaped cavity, the columns standing vertical to the planes of cooling.

Columnar structure, being mainly a result of contraction arising from cooling, is usually best developed in those portions of the magma exposed to the cooling effects of the atmosphere, and of the rocky surface on which the lava rests. Hence, in thick lava-flows this characteristic structure may be only developed in the upper and lower portions.

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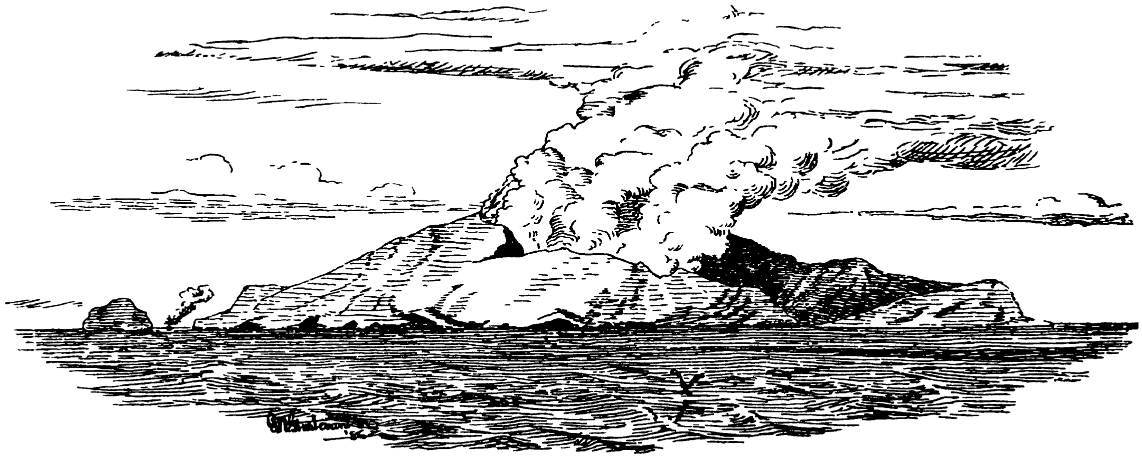

From a Sketch by Mrs C. Alma Baker.]

WHITE ISLAND, NEW ZEALAND. LOOKING NORTH-EAST—THREE MILES DISTANT.

The columnar structure is found in effusive igneous rocks of all kinds, but is most frequently seen in those of a basic type (figs. 124 and 125).

Pillow-Structure.—When a very fluid lava is chilled by contact with water, the surface sometimes assumes the appearance of a number of large pillows packed together. Pillow-structure is seen in lavas of all ages. Good examples may be seen in the sea-cliffs near Ballantrae,[1] in south-west Scotland, where a flow of basalt is intercalated with the Ordovician rocks; at Oamaru,[2] New Zealand, where a stream of basalt is associated with Middle Tertiary strata; and on the sea-coast of Savaii, where the recent lavas of the Matavanu volcano flow into the sea.

Dr. Tempest Anderson,[3] who was an eye-witness of the actual formation of this exceptional lava-structure, states that the lava, chilled by the waves,

FIG. 125.—Showing columnar structure of basalt, Giant's Causeway, Antrim, N. Ireland. (After Tempest Anderson.)

extended itself into lobes which, reduced to a pasty condition by cooling, would be seen to swell into buds with narrow necks, and these, being still in communication with the source of supply, would rapidly increase in heat, mobility, and size till they became lobes as large as a sack or pillow, or perhaps stopped short at the size of an Indian club or large Florence flask.

At Ballantrae the spaces between the pillows are filled with chert containing Radiolaria and graptolites, and at Oamaru with limestone mainly composed of Bryzoa and Foraminifera.

Spheroidal Weathering.—Rocks are frequently divided by two systems of joints, or by joints and the bedding-planes, into roughly cuboidal blocks. When water percolates along these planes, it decomposes the rock, changing it into clay. At the edges where two planes meet the action is twice as rapid as on the sides of the block; and at the corners where three planes meet, it is

[1] B. N. Peach and J. Horne, *The Silurian Rocks of Britain*, vol. i. Scotland; London, 1903.

[2] J. Park, "Marine Tertiaries of Otago and Canterbury," *Trans. N.Z. Inst.*, vol. xxxvii. p. 513; and "Geology of Oamaru District," *Bull. 20, N.Z. Geol. Surv.*, Wellington, 1918, pp. 36–41.

[3] Tempest Anderson, "Volcano of Matavanu in Savaii," *Quart. Jour. Geol. Soc.*, vol. lxvi. p. 633.

three times as rapid. This differential rate of weathering causes the edges and corners to become gradually rounded, and in time the block may assume a spheroidal form.

When the decomposition of the block is complete, as frequently happens near the surface of the ground, the rock is entirely changed into clay; but when incomplete, a rounded, boulder-like core of undecomposed rock may remain in the centre.

The rocks that are the most prone to *spheroidal weathering* are basalts, andesites, phonolites, granites, tufaceous sandstones, and greywackes; but such relatively soft rocks as mudstones and marly clays, that have been broken into small cuboidal blocks by shrinkage cracks, frequently exhibit this phenomenon in a perfect manner.

The clays resulting from the decomposition of rocks *in situ* are called *residual clays* to distinguish them from glacial clays, and the detrital clays that often accumulate on slopes and in hollows.

Spheroidal weathering is not always the result of aqueous decomposition. In regions where there is a considerable range of daily temperature, as in alpine valleys and arid highlands, angular blocks exposed at the surface soon assume a spheroidal shape. In this case the rounding is due to the stresses arising from the alternating expansion and contraction of the surface skin of the rock. If the intensity of stress on the sides of the block is represented by 1, that along the edges will equal 2, and at the corners or solid angles 3. Owing to the action of these unequal stresses the block peels off in wedge-shaped flakes and curved splinters, and the effect of this is to cause the block to assume a rounded shape, but without the formation of residual clays.

Amygdaloidal Structure.—A lava stream, through the expansive force of the escaping steam and gases, is usually made vesicular or scoriaceous at the surface and bottom. Later these bubble-cavities may become filled with mineral matter deposited from solution, constituting what is called an *amygdaloidal structure*. The amygdaloids[1] or almond-shaped blebs are obviously of *secondary origin*.

Fragmentary or Pyroclastic[2] Ejecta.—These rocks include the various fragmentary material ejected by a volcano, in the form of large and small *blocks*, *scoriæ*, *lapilli*, *ash*, and *dust*.

The *blocks* are mostly angular or subangular masses of lava that are often of enormous size. Rounded blocks are not at all rare. Among the blocks that are projected into the air many fall back into the throat of the vent, where they are churned up till again expelled. In this way the blocks that are not reduced to small fragments may be worn till they become well-rounded.

The cindery pieces of lava are called *scoriæ*; while the smaller scoriaceous fragments are usually spoken of as *ash*. The grit and dust are merely comminuted lava.

The small pieces of lava torn from the pasty lava form what are called *lapilli*, which range from the size of peas to that of walnuts. The larger masses of liquid lava that are projected from the vent solidify while swirling through the air, and thereby frequently assume a torpedo or bomb-like form with curious twisted ends; hence their name *volcanic bombs* (fig. 127).

The coarse angular blocks, when consolidated, form what is called a *volcanic breccia*. The pell-mell mixture of large and small blocks set in a matrix of grit and dust is usually called a *volcanic agglomerate*. The loose material that

[1] Gr. *amygdalon*=an almond, and *eidos*=like.
[2] Gr. *pŷr*=fire, and *klastos*=broken.

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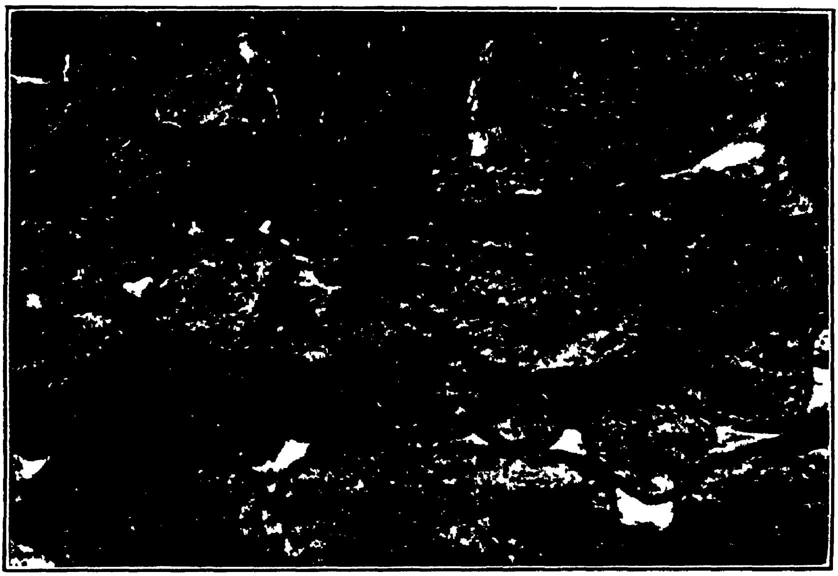
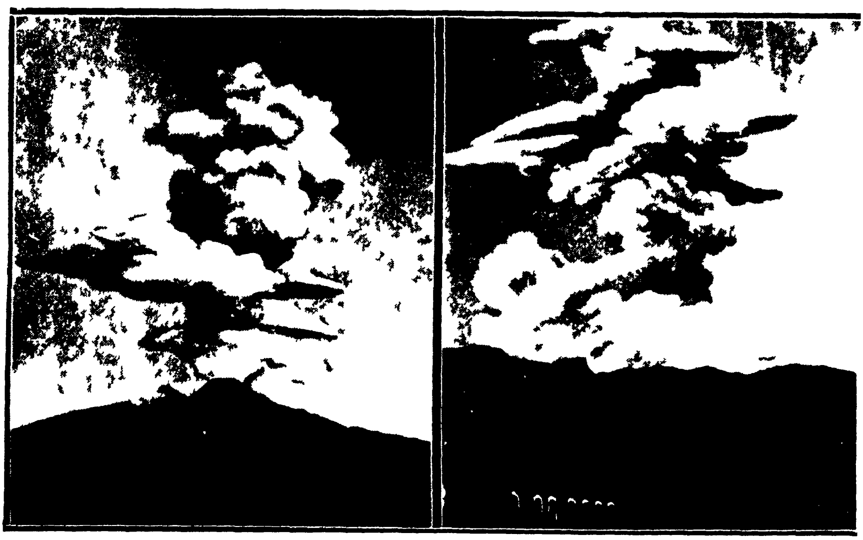


FIG. 126.—Showing pillow-structure at Cape Oamaru, New Zealand.

A B



C D

Cloud Forms—Eruption of Colimo Volcano, Mexico 1910
(Photographed from railway train during eruption)

A Form of steam cloud five minutes after first explosion
B At ten minutes
C At fifteen minutes
D At twenty minutes

blocked up the throat of an expiring or spent vent forms, when consolidated, an *agglomerate-neck*.

The finer material ejected by volcanic explosions is frequently subjected to a certain amount of wind sorting, and hence is frequently deposited in layers that often possess a well-stratified appearance. The layers of material ejected by a succession of explosive eruptions may form a series of parallel layers spread over the surface of the land. When the material in the different layers varies in texture, we get a deposit of volcanic origin that often presents the well-stratified appearance of aqueous sediments. Deposits of volcanic ash when consolidated form what is called *volcanic tuff*.

Most volcanoes occur near the sea, and many are actually situated on the sea-floor. Lavas that flow into the sea are sometimes broken up into blocks and sand by the explosive action of the stream suddenly generated on their surfaces. The lavas and ashes ejected by *submarine volcanoes* form *marine tuffs* that may be, in places, interstratified with the ordinary sediments of denudation.

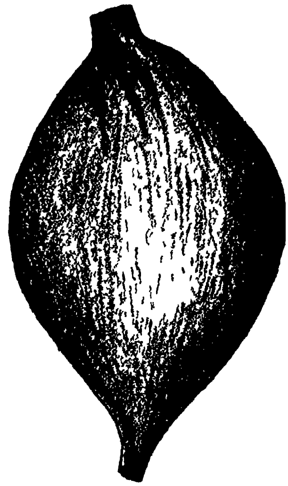


FIG. 127.—Showing volcanic bomb from Mount Eden. Auckland.

The ejecta from a land volcano may fall into the sea, or it may be carried into the sea by streams and rivers draining the eruptive area. When sorted and laid down in beds, this material may also form *marine tuffs*. Tuffs formed in this way may attain a considerable thickness, but they will always be confined to the neighbourhood of the eruptive area. At their edges they may be interbedded with ordinary sandstones, mudstones, or limestones. Sandstones containing a considerable proportion of fine volcanic material are called *tufaceous sandstones*. Marine tuffs, that were deposited slowly, and tufaceous sandstones are frequently fossiliferous.

The fragmentary material ejected by a volcano include blocks of granite, schist, slate, or other rock torn from the rocks through which the volcanic fissure passes. Among the debris ejected by Vesuvius, blocks of limestone are comparatively abundant.

Steam and Gaseous Emanations.—The principal product of many volcanic eruptions is steam. In the early stages of the eruption the steam rises from the crater in the form of a pillar, which is crowned with a cloud shaped like a cauliflower; in the later stages it spreads out into the well-shaped *pine-tree* form. These cloud-forms are well seen in Plate XVII., which shows an eruption of Colima volcano, in Mexico, in 1910. The cauliflower cloud was seen to develop rapidly into the pine-tree form.

Besides steam, many other vapours, including those of sodium chloride, iron chloride, chlorine, sulphuretted hydrogen, and sulphurous acid, that were dissolved in the molten magma, escape from fissures and cracks in the cooling lava. These imprisoned gases probably play an important part in causing the lava to well-up in the crater vent. For the most part they escape when the lava reaches the surface. The gases that remain entangled in the lava expand and form rounded cavities, called gas-bubbles, that cause the upper portion of the stream to be vesicular and scoriaceous.

The exhalations in the first stages of cooling are mainly the chlorides of sodium and iron, and in the later stages sulphuretted hydrogen and sulphurous

acid. In volcanic regions the characteristic smell of sulphurous acid, SO_2, pervades the atmosphere at all times, more particularly in regions where volcanic activity is on the wane.

The fissures from which gaseous emanations escape are called *Fumaroles*, the walls of which are frequently lined with beautiful incrustations of sulphur crystals sublimed by the interaction of H_2S and SO_2.

Expiring Volcanic Activity.—A volcano in the waning stage of its existence may emit only steam and various gases. The well-known decadent volcano Solfatara, near Naples, emits only steam and gases; hence any volcano in this phase of activity is said to be in the *Solfataric* stage.

Thermal Springs.—In some regions of waning volcanic energy, the old craters are honeycombed with underground passages from which openings rise to the surface, where they usually terminate in basins filled with clear bluish-green mineralised waters, the majority of which are hot or boiling furiously.

The basins are usually situated on the summit of low mounds composed of siliceous sinter of various hues deposited by the over-flowing waters when they come in contact with the air. The largest groups of thermal springs are those of the Yellowstone National Park, U.S.A., and Roturua, N.Z. At the latter region some of the springs are strongly alkaline, and others strongly acid. They all possess valuable therapeutic properties.

Geysers.—These occur in volcanic regions where the rocks, some little distance below the surface, are still intensely hot, and within the reach of springs or streams of water. They are connected by a fissure with a pool or basin from which the water at certain intervals is ejected with great force, frequently to a height of several hundred feet.

The principle underlying the intermittent action of geysers[1] is dependent on the expansive force of superheated steam. The fissure becomes filled with a column of water from the overflow of some neighbouring spring or stream. The heat is greatest in the lower part of the fissure; consequently the water in that part becomes hot, and soon reaches a temperature of 212° Fahr. The water would boil at that temperature at the surface, but owing to the hydraulic pressure of the column of water, it does not boil. On the contrary, it becomes hotter and hotter till in some part of the fissure the boiling-point corresponding to the pressure is reached. The steam thus generated expands and pushes some of the water out at the surface. This relieves some of the pressure, with the result that the water below boils furiously. Steam is now generated with great rapidity, and, exerting enormous expansive force on the column of water, with a mighty roar, hurls it into the air together with any loose stones that may lie in its path.

Some geysers play at short intervals, while others are quiescent for days and even weeks. A geyser may be made to play before its customary time by the application of soap, which reduces the surface tension or strength of the resistant skin of water.

Distribution of Volcanoes.—If we look at a map of the globe, we are at once confronted with the significant fact that almost all recent indications of volcanic activity are to be found either along certain lines of coast or in islands. Most noticeable of all is the ring of volcanoes that fringes the great basin of the Pacific Ocean. This encircling girdle extends along the whole length of the Andes from Tierra del Fuego to Central America, whence it follows the coastal Sierras to the Aleutian Islands; from there passing southward to Kamtschatka, Kurile Islands, and Japan; thence stretching through the Philippines, Sumatra, Java, and adjacent islands to New Zealand.

[1] Ice. *geyser*=gusher or roarer.

Another remarkable zone of volcanoes girdles the globe from Central America eastward to the Azores, Canary Islands, Mediterranean, Red Sea, and through a chain of islands to the mid-Pacific and New Zealand group.

Origin of Volcanoes.—It will be observed (*a*) that the distribution of active volcanoes is linear, and (*b*) that volcanoes rise either directly from the floor of the ocean or lie within a moderate distance from its coasts or of large sheets of water.

The linear distribution of volcanoes seems to warrant the inference that some connection exists between volcanic vents and crustal lines of weakness, this perhaps arising from the circumstance that denudation has weakened the arches of the great mountain-making folds. The coastal or oceanic situation of many vents would lead to the further inference that eruptions may be dependent on the presence of water. The absence of volcanoes in the Ural and Himalaya Mountains seems to support this view.

Active volcanoes usually occur on the crests of terrestrial ridges, which supports the view that *ridges of elevation* resulting from folding are lines of crustal weakness. Further support of this contention is obtained from the gravity observations made in India and the United States. These observations show that mountain masses, such as the Himalayas, do not produce in the direction of gravity the effect that their visible mass should produce. In other words, they are deficient in density.[1]

If the elevation of great earth flexures produces the lines of weakness, we cannot doubt that the immediate cause of volcanic activity is the expansive force of steam generated at enormous pressures from contact with heated rocks below. The origin of this magmatic water is still problematical. According to some, it finds its way below by seepage from the floor of the sea ; according to others, it is *juvenile*—that is, an original constituent of the molten magma. Whatever its origin, its presence will render the magma more fluid, and since it must exist under enormous stress, it will cause the magma to penetrate every plane of weakness produced by the folding. Where the plane of weakness coincides with a ridge of elevation, we shall obtain a manifestation of the phenomena known as volcanic activity.

Another conception is that the differentiation of the magma in connection with its cooling is the cause of volcanic activity, as many volcanoes have yielded a varying sequence of acid, intermediate, and basic rocks in their different eruptions. The paroxysmal eruptions are brought about by the gaseous elements of the magma.

The great mountain-building folds of the globe are meridional, *e.g.* Andes and Rocky Mountains; or equatorial, *e.g.* Alps, Caucasus, and Himalayas; and it is only on the meridional folds or their prolongations that we find the evidences of crustal weakness as expressed by volcanic activity. There are some exceptions, *e.g.* the volcanoes of the Caucasus. The north and south chains are everywhere crowned with active volcanoes, while the east and west chains are singularly free from volcanic phenomena.

Former Volcanic Activity.—Piles of volcanic rocks are found interbedded with stratified formations of nearly all ages, and so far as we can form an opinion, the various types of eruption and the character of the lavas, dust, scoriæ, and other solid ejecta did not differ from those of the present day.

Some of the outbursts that took place in the Middle and Older Palæozoic

[1] G. K. Gilbert, "Interpretations of Anomalies of Gravity," Prof. Paper 85–C., *U.S. Geol. Surv.*, 1913, pp. 29–37; R. D. Oldham, *Mem. Geol. Surv. India*, vol. xliii. part 2, 1917; and Sir Sidney Burrard, Prof. Paper No. 17, *Geol. Surv. India*, 1919.

eras were on a stupendous scale, and have only been paralleled by those of the Middle Tertiary.

In the Mesozoic era, there was a singular, almost world-wide, interval of quiescence, not without exceptions (Western South America, at the close of the Jurassic, Trias of the Southern Alps, etc.); but with the close of the Cretaceous, there came a remarkable revival of activity which probably attained its greatest intensity in the Miocene. Since then volcanic outbursts have become less and less violent, and narrower in their radius of disturbance. It would almost appear as if we were now living in a period of volcanic decadence.

The Lower and Middle Palæozoic and the Middle Tertiary were the great mountain-building periods of the globe, and also of maximum volcanic activity, not considering the pre-Cambrian with its vast intrusions and eruptions, and its general folding of all rocks. The coincidence may be more than accidental, and may be additional evidence of the relationship of orogenic folding and volcanic activity.

Old Land-Surfaces.—The old land-surfaces that existed between the different periods of activity can easily be traced in sea-cliffs and river-gorges. The layers of soil are usually baked and oxidised into reddish brick-coloured clays in which the remains of trees are found, in places converted into charcoal, or silicified into wood opal, while the peat-bogs have been converted into lignite.

The old land-surfaces that mark periods of quiescence between successive eruptions can be detected in many volcanic regions. The seams of lignite and beds of shale interbedded with the Tertiary volcanic rocks of the Isle of Mull and Hauraki Peninsula are a record of denudation and vegetable growth during a considerable cessation of volcanic activity.

SUMMARY.

(1) Volcanoes may be classed as *Extinct*, *Dormant*, or *Active*.

(2) Volcanic eruptions according to their character constitute three well-marked types—

> *Vesuvian* type, *i.e.* eruptions from a crater-vent.
> *Icelandic* type, *i.e.* eruptions from a fissure-rent.
> *Krakatoan* type, *i.e.* explosive eruptions.

(3) Active volcanoes are distributed along the crests of coastal chains, or they lie near large sheets of water. They are frequently situated on terrestrial ridges.

The linear distribution of volcanoes, and their proximity to the sea, would lead to the inferences (*a*) that they occur along lines of crustal weakness; and (*b*) that water in the form of steam plays an important rôle in their origin and eruptive force.

(4) The solid material ejected by volcanoes is mainly lava and such fragmentary matter as blocks, scoriæ, ashes, and dust. The gaseous products, in addition to enormous volumes of steam, are sodium and iron chlorides, chlorine, sulphurous acid, and sulphuretted hydrogen.

(5) When the crater-walls are weak, the lava may escape at points where in time lateral cones are built up.

(6) There is abundant evidence of volcanic activity throughout the whole of geological time, particularly in the Eozoic, Early and Middle Palæozoic, and Tertiary eras. In the Mesozoic there was an almost complete cessation of volcanic activity throughout the greater part of the globe.

(7) Solfataras, geysers, and hot springs are evidences of waning volcanic activity.

CHAPTER XVI.

IGNEOUS ROCKS.

Occurrence, Physical Characters, and Composition.

An igneous rock is one that has cooled from a molten condition.

The study of igneous rocks includes a consideration of the following points:—

(a) Mode of Occurrence.
(b) Texture.
(c) Composition.

Mode of Occurrence.—An uprising molten magma that issues from a vent or fissure and spreads over the surface is said to be *effusive*, and the portions that cool and solidify below the surface are called *intrusive*.

The *effusive* lavas that are extruded from a volcanic vent usually take the form of *streams*; while those that issue from fissure-rents may form *streams*, or they may first fill up the inequalities of the ground over which they flow and eventually spread over the country as wide *sheets*. A succession of very fluid lavas issuing from a fissure may build up a plateau as large as a State.

Intrusive rocks are not seen till laid bare by denudation. Their form is dependent on the shape of the pre-existing fissures or cavities which they fill, or of the cavities which they open for themselves by their eruptive force. Commonly they appear (a) as more or less vertical sheet-like veins called *dykes*; (b) as irregular sheets called *sills* or *intrusive sheets* that have been intruded along the bedding planes of stratified rocks; or (c) as more or less dome-shaped masses called *bosses* that have solidified in huge caverns at a considerable depth below the surface.

Thus, in the various forms assumed by eruptive rocks we have the basis of a convenient morphological classification that embraces all kinds of igneous rocks—

I. **Effusive.**—Streams and sheets of lava.
II. **Intrusive.**—Dykes, Intrusive Sheets or Sills, and Bosses.

Intrusive rocks are sometimes divided into two groups, namely—

(a) *Plutonic* or *Abyssal*, *i.e.* those that have solidified at a great depth.
(b) *Hypabyssal*, *i.e.* those that have solidified at a less depth.

The *plutonic* rocks are usually more coarsely crystalline in texture than the *hypabyssal*, but the two groups are not very well marked, except in the extreme types.

In fig. 128 we have two streams of lava, *a*, *a*, that issued from fissures, *b*, *b*; and three sills *c*, *c*, *c*, that forced themselves along the bedding planes of a calcareous sandstone.

It is obvious that if denudation were to remove the greater portion of the cone, *b*, *b* would appear as dykes penetrating the tuffs and sandstone ; and the

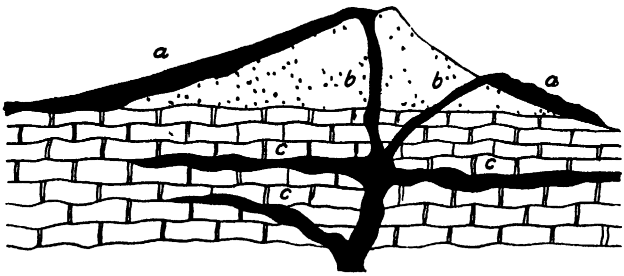


FIG. 128.—Showing lava streams *a*, *a*, and sills, *c*, *c*.

outcrop of the main dyke would not improbably be somewhat like that of the dyke shown in fig. 129.

FIG. 129.—Showing dyke penetrating tuffs at Kiama, N.S.W. (After Jaquet.)

Dykes, it should be noted, may vary from an inch or less to many thousands of feet in width. When the dyke-rock is harder and more resistant than the rock it penetrates, it may be left standing above the general level of the ground as a conspicuous wall ; hence the origin of the name *dyke*. On the other hand, if softer than the enclosing rock, it may be worn away so as to expose the dyke-fissure, as shown in fig. 129.

When the magma rises through a pipe-like fissure, as it frequently does in volcanoes, the mass which solidifies in the pipe forms what is called a *volcanic neck.*

When a *sill* widens out to a dome-shaped mass lying between two beds, it is called a *laccolith.*[1] This form of intrusion has a limited lateral extension, and usually arches and disrupts the overlying strata in making room for itself (figs. 130, 137).

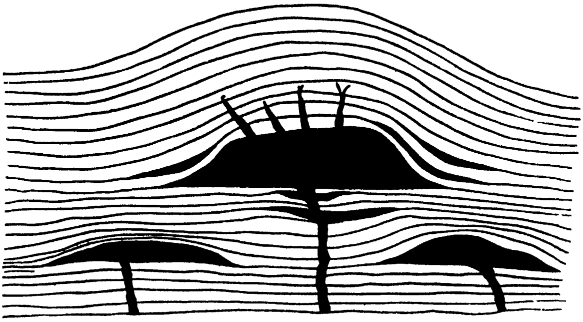


FIG. 130.—Showing dome-shaped sills or laccoliths. (After Gilbert.)

The intrusive *boss*, sometimes called a *batholith*, occupies a deep-seated cavity of irregular shape, and usually of large dimensions, frequently many miles across. The plutonic types of granite, syenite, diorite, and gabbro usually occur as bosses.

Obviously, then, the self-same magma, according to the situation in which it cooled and consolidated, may be an *effusive* lava, or an intrusive *dyke*, *sill*, or *boss*.

Relationship of Internal Structure to Rate of Cooling.—The texture of an

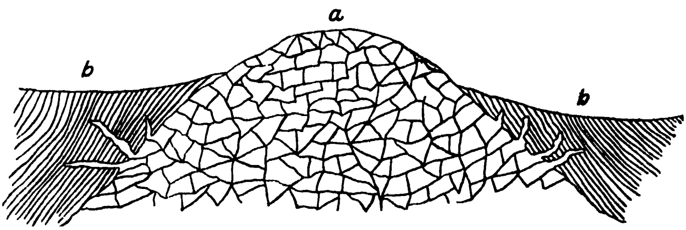


FIG. 131.—Showing intrusive boss exposed by denudation.
(*a*) Granite. (*b*) Slates.

igneous rock is not dependent on the composition of the original magma, but is mainly determined by the rate and conditions of cooling and consolidation.

The rate of cooling will mainly depend on the mode of occurrence of the eruptive magma. A lava stream, for example, will cool rapidly on the surface, at the selvages, and wherever it flows into a sheet of water. Moreover, a thin stream will cool more rapidly than a thick one. The magma that forms dykes and sills will cool more slowly than effusive lavas, and bosses more slowly than dykes. The relationship existing between mode of occurrence and

[1] Gr. *lakkos*=cistern, and ,

texture is so intimate and well ascertained that when one of these is given, the other can be postulated within narrow limits of error.

Dykes and intrusive sills have cooled slower than lava streams, and more rapidly than bosses lying far below the surface. Moreover, dykes and bosses have not only cooled slowly but also under great pressure, the latter arising mainly from (*a*) the weight of the enclosing and overlying rocks, and (*b*) the internal stress of the imprisoned gases and steam occluded in the magma and the molecular stress arising from crystallisation.

A molten magma does not differ from a furnace slag; hence, when it cools rapidly it forms a glass. When it cools slowly a crystalline structure is developed; hence, according to the rate of cooling, a given eruptive magma may present every variety of texture from the glassy to the completely crystalline.

A magma may become—

(1) *Wholly glass* when it cools rapidly.
(2) A *glassy matrix* with a few small imperfectly formed crystals when it cools less rapidly.
(3) *A glassy matrix* crowded with large crystals when it cools slowly
(4) *A matrix of minute crystals* with large crystals when it cools more slowly.
(5) *Completely crystalline*, i.e. *holocrystalline*, when it cools still more slowly.

A glass is a vitreous [1] body. If it is partially crystallised, it is said to be *partially devitrified* Devitrification is merely a process of crystallisation, and when the glass has been entirely replaced with crystals, it is *completely devitrified*.

The slower the rate of cooling, the more is the glassy matrix replaced by a crystalline structure, till a point is reached at which the ground-mass is wholly crystalline.

Generally speaking, the slower the cooling, the larger will be the crystals.

The incipient forms of crystals that first appear in a cooling glassy magma are minute rods and plates called *crystallites*. These form the framework of crystal-skeletons If the cooling is rapid, they are unable to arrange themselves in geometrical forms, but if the cooling is slow, they build up large crystals.

The crystallites frequently form beautiful radiating clusters. When grouped in spheres, they form what are called *spherulites*.

Frequently in glassy rocks the crystallites arrange themselves with their longer axis parallel with the *flow-structure*.

A glassy lava may sometimes be crowded with small enamel-like globules with an imperfectly developed concentric structure. This structure is called *perlitic*, and is not infrequently seen in acid lavas that have cooled more slowly than *obsidian*.

When conspicuous crystals of some mineral are enclosed in a finely crystalline ground-mass, the rock is said to be *porphyritic*, and the large crystals are called *phenocrysts*. The porphyritic structure is characteristic of the volcanic rocks, which usually exhibit two generations of the same minerals—an older one, the phenocrysts, and a younger one, the minerals of the ground-mass.

When a phenocryst is bounded by crystal faces, it is said to be *idiomorphic*.[2]

A rock in which the majority of the constituent minerals are idiomorphic is said to possess a *panidiomorphic* structure.

[1] Lat. *vitrum*=glass.
[2] Gr. *idios*=distinct, and *morphe*=shape.

FIG. 132.—Showing spherulites in a rhyolite.

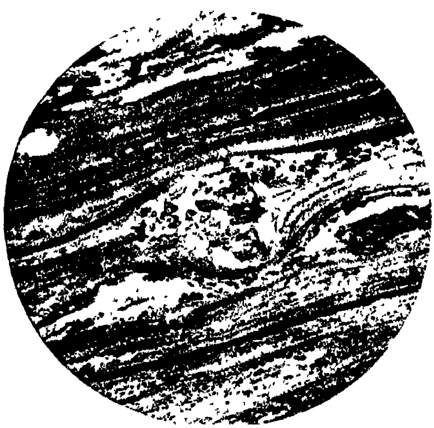


FIG. 133.—Rhyolite showing flow-structure.

Should only some of the crystal faces appear, which is frequently the case with the minerals that are the first to crystallise after the phenocrysts, the structure is called *hypidiomorphic*.

In most holocrystalline rocks, owing to crowding and mutual interference, the minerals do not often assume geometrical forms, and are then said to be *anhedral*[1] or *allotriomorphic*, their shape being determined by their surroundings.

One mineral may penetrate another, and intergrowths of minerals are common, arising from simultaneous crystallisation.

Composition.—A rock magma may be defined as a solution of silicate-minerals; that is, of silica or silicic acid, SiO_2, combined with various oxides of the metals called *bases*. The bases with which silica combines most abundantly are—

(1) Alumina	=aluminium sesquioxide	$=Al_2O_3$.
(2) Iron oxide	=iron protoxide	$=FeO$.
(3) Lime	=calcium oxide	$=CaO$.
(4) Magnesia	=magnesium oxide	$=MgO$.
(5) Soda	=sodium oxide	$=Na_2O$.
(6) Potash	=potassium oxide	$=K_2O$.

The great mass of igneous rocks is made up of a few minerals which are vastly more abundant than all the others put together. These few are *quartz*, the *felspar minerals*, the *ferro-magnesian minerals*, and the *iron oxides* as under—

Quartz, ...	As free silica.
Felspars, ...	Orthoclase, Monoclinic. Plagioclase, Triclinic.
Felspathoids, ...	Leucite and nepheline, alkali minerals.
Ferro-Magnesian Minerals, .	Pyroxenes, amphiboles, and micas.
Iron Oxides, ...	Magnetite (Fe_3O_4) and hæmatite (Fe_2O_3). These occur as *free or uncombined bases*.

The leading pyroxene minerals are *augite*, *diallage*, *hypersthene*, and *enstatite*.

The principal member of the amphibole group is *hornblende*.

The most abundant *micas* are *biotite* (a black mica), and *muscovite*, a clear transparent variety.

The felspars are silicate compounds in which iron is absent. The ferro-magnesian minerals are silicate compounds in which iron plays an important part.

Chemical analysis shows the respective amounts of silica and bases present, and enables the following convenient grouping of igneous rocks to be made on a silica basis:—

I. **Acidic Group,** with 65–80 per cent. of silica; and S.G. below 2·75. Typical rocks—Granites, rhyolites, felsites.

II. **Intermediate Group,** with 66–52 per cent. of silica; and S.G. between 2·70 and 2·80. Typical rocks—Diorites, andesites.

III. **Basic Group,** with 45–60 per cent. of silica; and S.G. between 2·80 and 3·00. Typical rocks—Gabbros, dolerites, basalts.

IV. **Ultra-basic Group,** with less than 50 per cent. of silica; and S.G. between 2·85 and 3·40. Typical rocks—The peridotites.

In each group the balance is represented by bases.

In the *Acidic rocks* we have at the lowest limit 65 per cent. of silica and

[1] Gr. *a*=without, and *hedron*=face.

35 per cent. of bases. Thus it happens that there is more silica present than what is required to combine with the bases. The silica remaining uncombined after satisfying the bases is termed *free* silica, which appears in the rock in the form of quartz. Hence we find that all *acidic* rocks contain a proportion of free silica or quartz.

In the *Intermediate rocks* or *semi-basic*, the silica present about balances the bases; hence, in these, free silica is not often present; or, if present, it is usually in small amount.

In the *Basic* and *Ultra-basic* rocks, the bases predominate and free silica is absent.

Alteration of Igneous Rocks.—This is mainly effected by moist air, rain, or underground water containing carbonic acid and oxygen, or by thermal waters and acid vapours.

The crystalline minerals are hydrated, broken up, or replaced with other compounds. Among the first to break up are the felspars, which are converted into kaolin and mica. The felspars, when kaolinised, become cloudy, milky, and opaque.

Augite and hornblende become converted into calcite, chlorite, and magnetite; and olivine into serpentine.

The hydration and alteration of the felspars also gives rise to a very characteristic family of secondary crystalline minerals called *Zeolites*, which are mainly hydrous silicates of alumina and alkalies. The zeolites occur mostly encrusting or coating the walls of cavities, cracks, and veins in basalt, andesite, phonolite, and other volcanic rocks, and occasionally in granite and gneiss.

The more common zeolites are *natrolite*, *analcime*, *stilbite*, and *prehnite*.

The minerals that separate out of the molten magma are called *primary*, and those that result from the alteration or decomposition of the consolidated rock, *secondary*.

Secondary minerals are also introduced into a rock by infiltration. For example, the amygdaloids that fill the bubble-cavities in a vesicular lava are secondary.

Petrographical Provinces.—A petrographical province is part of a larger region in which the rocks exhibit certain points of resemblance due to some real genetic relationship or community of origin. It is easily conceivable that the lavas extruded from a common reservoir should be related, even though the points of emission might be far apart.

Magmatic Differentiation.—At one time it was believed that lavas were extruded in an orderly succession, beginning with acidic rocks and ending with basic. Acidic lavas were thought to characterise the earlier outbursts; intermediate lavas the maturer periods of activity; and basic lavas the expiring or waning phases.

All the lavas were believed to originate in a common stock-magma, and the different rock-types were supposed to be due to a process of magmatic differentiation. The idea probably originated in the supposition that the molten magma arranged itself in horizontal layers or zones of different density, the lighter acidic glass forming the top layer and the basic the lower, like the charge from a blast-furnace, which separates itself into slag and regulus when poured into a mould.

Later investigation has shown that while this orderly succession of acidic, intermediate, and basic lavas characterises many regions, the exceptions are so numerous that magmatic differentiation cannot be regarded as a law of effusion of general application.

So far as we can determine, a magma, before eruption, is a solution of rock-forming constituents highly charged with gases and aqueous vapour. With decrease of pressure the gases and water are largely expelled and a viscous magma remains. If the magma reaches the surface as a lava and cools rapidly it may solidify as a more or less homogeneous unit, forming a glass in which no constituent minerals can be detected; but if the rate of cooling is slow, the constituent minerals will separate out, forming a crystalline mass. Due to various rates of cooling, there are many conditions between these extremes, ranging from a glass containing widely scattered crystals to a crystalline mass in which only a small amount of residual glass remains as a ground-mass.

In the original magma the rock-forming minerals are mutually miscible. If they were not, they would separate out into layers in accordance with the well-known principle of liquation.

Pressure raises the melting-point of fused minerals, but the occluded gases and water tend to make the magma more fusible. With decrease of pressure and expulsion of gases and water, if the rate of cooling be slow, the minerals will separate out in a more or less orderly procession. First will appear the accessory oxide minerals—magnetite, chromite, etc.; then the silicates, forming the ferro-magnesium minerals; and, lastly, the felspars. This orderly fractional crystallisation seems to be closely related to the rate and conditions of cooling. As each crop or fraction of crystalline minerals separates, the remaining liquid mass will possess a composition differing widely from that of the original magma.

The cooling of a magma will begin along its walls and borders, hence it is there that the crystalline minerals will first appear. In a fluid mass these minerals will sink and become dissolved or reabsorbed, and this will continue till the saturation point is reached, when aggregates, mainly of the iron minerals, will be formed. Fractional crystallisation would thus seem to be a process of magmatic differentiation.

At the present time the laws governing magmatic differentiation are not well understood. So far, the results obtained from experimental research are meagre and inconclusive. In his discussion on the nature of "glass-base" or ground-mass, Lagorio,[1] in 1887, called attention to Soret's hypothesis of molecular diffusion, which postulated that when two parts of the same solution are at different temperatures there will be a concentration of the dissolved substance in the cooler portion. It was thought that the substances with which a magma was most nearly saturated would tend to accumulate at the cooler points, thereby leaving an excess of the solvent materials in the warmer portions.

Becker [2] showed that to obtain magmatic differentiation in such a viscous medium as a molten magma by a process of molecular diffusion would require almost unlimited time; while Bäckström [3] pointed out that although molecular diffusion might cause changes in the absolute concentration, it could no more alter the relative proportions of the dissolved substances than it could in a mixture of gases.

It has been urged by some writers that the assimilation of foreign material may play a more or less important part in the differentiation of magmas. The molten mass as it rises from sub-crustal depths is enclosed by walls of rock upon which it must exert a solvent action. The extent of this action will depend on the composition of the magma, the composition of the wall-rock, the temperature of the magma, and the pressure.

The wall-rocks may be igneous or sedimentary, or partly igneous and partly sedimentary; and they may be acidic or basic. If the magma is saturated with respect to the constituent substances of the wall-rock, the solvent action will be slight; if unsaturated, its activity may be considerable. A basic magma should absorb silica, and an acidic magma should absorb bases. The process of assimilation of wall-rock is regarded by Johnston-Lavis [4] and Lœwinson-Lessing [5] as an important factor in magmatic differentiation. More recently Daly [6] has urged what he calls *magmatic stoping* as a process of igneous intrusion.

He supposes that a deep-seated magma eats its way upward by its solvent action on the invaded rocks. In this way the composition of the magma is continually changing. Daly contends that such a magma, by a process of *gravitative adjustment*, will separate into layers, the denser below, the lighter above. Vogt [7] regards the assimilation hypothesis as untenable, but it has received the support of some well-known writers. Michel-Lévy [8] argues that differentiation may be brought about chiefly by the circulation at high temperatures and

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[1] A. Lagorio, *Min. pet. Mitt.*, vol. viii., 1887, p. 421.

[2] G. F. Becker, *Am. Jour. Sci.*, 4th series, vol. iii., 1897, p. 21.

[3] H. Bäckström, *Jour. Geol.*, vol. i., 1893, p. 773.

[4] H. J. Johnston-Lavis, "The Ejected Blocks of Monte Somma," *Trans. Edin. Geol. Soc.*, vol. vi., 1892–93, p. 314.

[5] F. Lœwinson-Lessing, *Compt. rend.*, 7. *Cong. géol. internat.*, 1897, p. 300.

[6] R. A. Daly, *Am. Jour. Sci.*, 4th series, vol. xv., 1903, p. 269; vol. xvi., 1903, p. 107.

[7] J. H. J. Vogt, *Die Silikatschmelzlösungen*, part ii., 1904, p. 225.

[8] A. Michel-Lévy, *Bull. Soc. géol. France*, 3rd series, vol. xxv., 1897, p. 367.

under great pressure of the gases and aqueous vapour contained in the magma. These agents may entangle certain constituents (the more easily sublimable oxides and silicates together with decomposable fluorides and chlorides) and concentrate them in the upper layers of the magma, thereby leaving the ferro-magnesian minerals in greater proportion in the lower portion.

According to this hypothesis, in the order of ejectment the later lavas should be more basic than the earlier.

Of the many conditions that tend to bring about magmatic differentiation, pressure is probably not the least important. Schweig,[1] who has taken pressure into account, argues that in a molten magma, under great pressure, partial crystallisation takes place. The crystals thus formed sink into the fluid mass, while the mother liquor accumulates above them. When an eruption takes place the mother liquor is ejected, and with the consequent relief of pressure the fusibility of the separated crystalline matter is increased. The latter is re-absorbed, and may be expelled by a later eruption; and in this way the magma, originally homogeneous, may give rise to two or three different lavas emitted from the same vent. That is, fractional crystallisation is aided by gravity; and then, under reduced pressure, the crystalline layer again liquefies.

In his memoir on the Highwood Mountains, Pirsson [2] discusses *fractional crystallisation*, and shows how convection and crystallisation may go on together. In a general way it may be assumed that the less soluble and less fusible substances will be formed earliest; hence the so-called accessory minerals of a rock will be among the first separations.

The Atlantic and Pacific Types of Igneous Rocks.—The genesis of igneous magmas is still so obscure that all attempts to formulate a satisfactory genetic classification have ended in comparative failure, and the solution of the difficulty seems no nearer now than half a century ago.

Among the attempts in this direction, the Cretaceous and Tertiary igneous rocks have been divided into two main groups representing two great petrographical provinces, namely, *alkalic* and *calcic*, the former characterising the Atlantic type of coast-line, the latter the Pacific type.

Becke has advanced the postulate that alkalic rocks are typically associated with subsidence due to radial contraction of the globe; and the calcic with orogenic [3] folding arising from lateral compression. The volcanic islands scattered throughout the Atlantic are, he conceives, merely remnants of a once extensive tract of alkalic rocks now occupied by the Atlantic depression. On the other hand, the Pacific is fringed with a remarkable ring of andesitic rocks of the calcic type, and this encircling ring would seem to be connected with the uplift of the great crustal folds that girdle the Pacific coast-line.

The alkalic and calcic grouping has been extended so as to embrace the older plutonic rocks, the Atlantic group including the alkali-granites, nepheline-syenites, etc.; and the Pacific group the granites, quartz-diorites, gabbros, and norites.

In the main, the alkalic or Atlantic type of rocks occurs towards the Atlantic sea-board in both the American and Eurasian continents; and the calcic or Pacific towards the Pacific sea-board. Singularly enough, in Galapagos, where the Atlantic and Pacific come near one another, the types are curiously interwoven. In New Zealand, where we should look for the Pacific type alone, there is a curious commingling of the calcic and alkalic types in the small petrographical province of Otago Peninsula, on the east coast of the South Island; but in the greater petrographical provinces of Taranaki, Taupo, and Hauraki, in the North Island, the rocks belong to the Pacific group. Henry S. Washington contends that the contrast between the alkalic and the calcic magmas is not so great as hitherto believed.[4] The two Atlantic and Pacific tribes are,

[1] Martin Schweig, *Neues Jahrb.* Beil. Band. xvii., 1903, p. 516.

[2] L. V Pirsson, *Bull. U.S. Geol. Survey,* No. 237, 1905, p. 183.

[3] Gr. *oros*=a mountain, and *genesis*=origin or creation.

[4] "The Volcanic Cycles in Sardinia," *Congr. Géol. Internat.*, XII. Sess. (Canada), pp. 235–238, 1914.

he thinks, inadequate, and von Wolff has already instituted a third tribe, the Arctic, to embrace purely basaltic regions.

It is noteworthy that in the South Pacific Ocean, which is thickly dotted with groups of small islands in a way that would suggest a continental subsidence of the Atlantic type, the Hawaii, Tahiti, Cook, and other islands are largely composed of alkalic volcanic rocks.

Dr. Flett has suggested a third group, the *spilitic suite*, consisting of the pillow-lavas and their associates occurring in the Dalradian schists of Scotland and in the Ordovician of the Southern Uplands of that country. The spilites appear to be normal basalts in which the soda molecule has been concentrated by some kind of differentiation.

The alkali and the calcic types are conceived by Harker to be dominant elements in tectonics, and related to the development of certain crustal features. They are conceived on too broad a basis to be adaptable for the requirements of a general classification of igneous rocks.

Professor Daly [1] has shown that quantitatively the alkaline rocks of North America amount to less than one-tenth of 1 per cent. of all the igneous rocks, perhaps even less than this, and that of Europe to less than 1 per cent. From this it would appear that the rôle played by the alkaline rocks in crustal tectonics must be relatively insignificant.

Classification of Igneous Rocks.—After nearly a century of investigation, no classification has been formulated that is generally accepted as a recognised standard, or that is satisfactory alike to the field-geologist and the laboratory student. The first attempts at classification were based on *megascopic* character—that is, on outward appearance of the rock, as seen in the field and in hand specimens. About the middle of the nineteenth century there came a better knowledge of the mineralogical characters of rocks, which soon led to a recognition of the prominent part played by the felspars. Since then the felspars have been an important factor in all modern classifications of igneous rocks.

The first great advance in petrography was the introduction of microscopical methods of investigation, the value of which was fully recognised before the advent of the seventies. The importance attached to this new branch of investigation was so overwhelming that for several decades there was a tendency among writers to place all other rock-characteristics in the background, and at one time there was a fear among field-geologists that the study of rocks would be altogether relegated to the laboratory. However, a reaction set in, and at the present time the importance of geological relationships, mode of occurrence, and formation are now recognised as no less important than mineralogical composition.

The classification of Rosenbusch, now widely adopted, divides igneous rocks into—

(1) Deep-seated or abyssal.
(2) Dyke rocks or hypabyssal.
(3) Volcanic rocks or effusive.

This grouping is intended to express a relationship between mode of occurrence and texture. Genetically all three types of rock may originate from the same magma.

Zirkel bases his classification of igneous rocks on (*a*) *mineral character*, (*b*) *texture*, and (*c*) *age*.

English writers have always strongly combated the age distinction of igneous

[1] R. A. Daly, *Igneous Rocks and their Origin*, New York, 1914.

rocks, it being held that igneous magmas of similar composition are alike when solidified in similar conditions, regardless of the epoch in which they were erupted.

The *mode of occurrence* of igneous rocks is dependent on local or regional crustal weakness, as indicated by the presence of fractures and fissures, and on certain dynamic conditions, the origin of which is still obscure.

The *texture* is merely an expression of the mode of occurrence.

The *composition* is independent of both mode of occurrence and its concomitant texture. For example, the same magma, according to some accident of local crustal weakness, may occur as a boss, a dyke, an intrusive sill, or an effusive lava—four well-marked morphological types that may differ in texture, but not in composition.

The following arrangement of igneous rocks is based on texture and mineralogical character, and is useful as showing the succession of related rock-families as we pass from the acidic to the basic.

Texture.	Acidic.	Intermediate.		Basic.
	Orthoclase.		Plagioclase.	
	Quartz.	Hornblende or Augite.		Augite or Olivine.
Glassy . .	Obsidian	Trachyte glass	Andesite glass	Tachylyte
Partly crystalline .	Rhyolite	Trachyte	Andesite	Basalt
Holocrystalline .	Granite	Syenite	Diorite	Dolerite

An acidic magma of uniform composition may give us a granite, rhyolite, or obsidian, according to the position in which it cooled and consolidated; and a basic magma, a dolerite, basalt, or tachylyte. The acidic rocks differ in mineralogical character and texture, but not in chemical composition; and this is also true of the basic and intermediate rocks.

The holocrystalline types of rock occur mainly as plutonic bosses, dykes, and laccoliths; the partly-crystalline principally as lava streams and sills; and the glassy as effusive lavas that have cooled rapidly.

Summary.

(1) The points that should be specially emphasised in connection with igneous rocks are—

(*a*) Mode of occurrence.
(*b*) Texture or grain.
(*c*) Composition.

(2) The same uprising molten magma, according to the situation in which it cools and consolidates, may form—

(*a*) An *intrusive boss* that penetrates the crust, crushing, disrupting, displacing, and perhaps even dissolving the rocks with which it comes in contact, but in no case reaching the outer surface.

(b) *Vein-like sheets*, called *dykes*, that fill fissures and cracks in the rocky crust.
(c) *Intrusive sills or sheets* that have forced their way along the bedding planes of stratified rocks.
A sill that has swelled out to a dome-shaped mass is called a *laccolith* (fig. 132). A large laccolith that is only partially uncovered is sometimes difficult to distinguish from an intrusive boss.
(d) An *effusive stream* of lava that issued from a vent or fissure.

(3) A molten magma is merely a natural slag or glass. If it cools rapidly it retains the glassy structure, but if slowly it develops a completely crystalline structure. Between the glassy and holocrystalline forms, we get an endless variety of rock-textures, varying according to the rate and conditions of cooling.

(4) A molten magma may be regarded as a solution of rock-silicates, and as it cools, the silicates separate out in crystalline forms. The principal constituents of igneous rocks are as under—

(a) *Quartz*, occurring free or uncombined.
(b) *Felspars*—Orthoclase and Plagioclase.
(c) *Felspathoids*—Leucite and Nepheline, both alkali minerals.
(d) *Ferro-magnesian minerals*, a group of great importance, including the augites, hornblendes, micas, etc.
(e) *Iron oxides*, mostly magnetite and hæmatite.

(5) The alteration of igneous rocks is mainly effected by water containing CO_2 and O, and by thermal waters and various gases.

The products of the alteration of primary minerals are called *secondary* minerals.

(6) *Petrographical Provinces* are regions in which the rocks exhibit certain points of resemblance.

(7) *Magmatic Differentiation* refers to the succession of acid, intermediate, and basic lavas that was at one time believed to represent the normal sequence of magmatic effusions in a given volcanic region, but other successions occur as often as this one. Some authors have urged that the assimilation of foreign material may play a rôle in the differentiation of magmas.

(8) The *Atlantic* or *Alkalic* and the *Pacific* or *Calcic* types of igneous rock represent two great petrographical provinces, the former characterising the Atlantic type of coast-line, the latter the Pacific type. These two groups of rock-types are believed to be related to the genesis of certain crustal features, the Atlantic group with depression, and the Pacific with orogenic folding.

Where the Atlantic and Pacific meet in Galapagos, there is a singular commingling of the alkalic and calcic types of rock.

(9) No satisfactory basis has, so far, been discovered for a genetic classification of igneous rocks. Most modern classifications are based on *mode of occurrence*, *texture*, and *composition*.

Based on mode of occurrence alone, we get

(a) Deep-seated or abyssal.
(b) Dyke rocks or hypabyssal.
(c) Volcanic rocks or effusive.

The *Deep-seated* or plutonic rocks are holocrystalline, the dyke rocks mainly holocrystalline, and the volcanic rocks partly crystalline and glassy.

According to their composition, igneous rocks are divided into four main groups as follows:—

(*a*) Acidic.
(*b*) Intermediate.
(*c*) Basic.
(*d*) Ultra-basic.

It must, however, be remembered that the study of rocks is more important than the formulating of a classification, the latter being of value only so far as it assists us in the systematic investigation of rock-masses.

CHAPTER XVII.

PLUTONIC, HYPABYSSAL, AND VOLCANIC ROCKS.

A.—Plutonic Rocks.

THE rocks of this type usually occur in bosses or boss-like protrusions that have evidently cooled at a considerable depth below the surface. Their presence is in every case revealed by the denudation of the overlying rocks ; and their actual extent is never known. They are *holocrystalline,* and in general the crystals are imperfectly formed owing to mutual interference. The presence of water and gases in the crystals would tend to show that the process of crystallisation took place under great pressure.

The distinctive feature of these abyssal rocks is their coarsely crystalline texture.

Sequence of Crystallisation.—In plutonic rocks which from their deep-seated character have necessarily cooled very slowly, there has been recognised a normal order of separation for the crystalline constituents which, although not invariable, is sufficiently general to warrant the broad generalisation of Rosenbusch that the order of crystallisation follows a law of *decreasing basicity,* as follows :—

I. (*a*) *Minor accessory minerals*=Apatite, zircon, sphene, garnet ; (*b*) *Iron ores*=Magnetite, hæmatite, pyrite.
II. *Ferro-magnesian minerals*=Olivine, hypersthene, enstatite, augite, hornblende, biotite, muscovite.
III. *Felspar minerals*=(*a*) Plagioclase ; (*b*) Orthoclase.
IV. (*a*) *Quartz* ; (*b*) *Microcline.*

It will be observed that the basic accessory minerals and iron-ores appeared before the ferro-magnesian minerals that play so conspicuous a part in plutonic rocks. After the complex silicates follow the felspar minerals that are devoid of iron ; and after these come quartz and, finally, microcline.

Varieties of Structure.—The principal textures met with in plutonic rocks are—

(*a*) *Granitoid, i.e.* like that of an ordinary granite.
(*b*) *Granulitic, i.e.* consisting of small grains of even size, imparting a granular appearance.
(*c*) *Pegmatitic, i.e.* strikingly coarse-grained, as found in typical pegmatite.
(*d*) *Porphyritic, i.e.* where conspicuous phenocrysts occur in a ground-mass of small crystals.
(*e*) *Graphic,*[1] *i.e.* a structure depending on the intergrowth of two essential minerals, and so named from its resemblance to Hebraic writing.

[1] Gr. *grapho*=I write.

It commonly arises from the interpenetration of felspar by quartz. This structure is usually on a microscopic scale, and hence is often called *micrographic*.

(*f*) *Gneissic*, *i.e.* when the constituent minerals exhibit a tendency to aggregation in parallel bands, arising partly from the flowing movement of the parent magma, and partly from subsequent rearrangement due to pressure and heat.

Principal Plutonic Rock Types.

Plutonic:
1. Granite—Acidic.
2. Syenites } Intermediate.
3. Diorites }
4. Gabbros } Basic.
5. Norites }
6. Peridotites—Ultra-basic.

ACIDIC PLUTONICS.

Granites.—These consist of rocks in boss-like masses from which veins or dykes may extend into the adjacent rocks.

FIG. 136.—Photomicrograph of granite, near Dublin. ×12. (After Grenville A. J. Cole.)

(*b*) Brown mica (biotite).
(*m*) Muscovite, a hexagonal section of this mineral occurs near top of section.
(*o*) Orthoclase. (*q*) Quartz.

The colour of granite is mainly dependent on the hue of the felspar, and is usually light or dark grey, pink, or reddish. The felspar usually shows cleavage-planes or crystal faces, and is thereby easily distinguished from the quartz, which possesses no cleavage, and usually occurs in irregular grains. The mica occurs in thin flexible scales. Orthoclase is the essential felspar, but a little accessory plagioclase is nearly always present.

The leading types of granite are—

(*a*) *Granite*=quartz, orthoclase, and two micas; one muscovite mica, the other biotite (fig. 136).
(*b*) *Biotite-granite*=a granite in which there occurs only brown mica, biotite.
(*c*) *Hornblende-granite*=a granite in which the mica is wholly or partly replaced by hornblende.
(*d*) *Pegmatite*=a strikingly coarse-textured granite which commonly occurs in veins in ordinary granite, or on the borders of granite bosses.
(*e*) *Greisen*=a granite changed by the final differentiates of the acid magmas and consisting only of quartz and mica.

A normal granite containing tourmaline may be called a *tourmaline-granite*.

When a granite contains conspicuous phenocrysts of felspar, it is said to be *porphyritic*, and in this case the rock may be called a *granite-porphyry*.

FIG. 137.—Showing Bear Butte Laccolith, Black Hill, S. Dakota, *U.S. Geol. Surv.* (After Jagger.)

Many granitic rocks contain irregularly rounded or ovoid patches of a darker colour and finer grain than the enclosing rock. These patches are called *basic secretions*. They contain the same minerals as the parent rock, and are supposed to be the earlier products of crystallisation.

INTERMEDIATE OR SEMI-BASIC PLUTONICS.

Syenites.—These are coarse to fairly fine-grained holocrystalline rocks with a granitoid structure. In a general way they may be defined as granites without

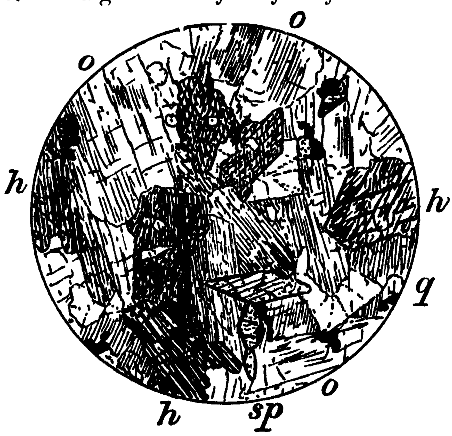


FIG. 138.—Showing syenite from Plauenscher Grund, Dresden. $\times 8$.

(*h*) Green hornblende. (*q*) Accessory interstitial quartz.
(*o*) Orthoclase fairly prismatic in habit. (*sp*) Sphene.

free quartz. They occur in the form of bosses and dykes, but are much less common than granite. The leading types are as follows :—

(*a*) *Hornblende-syenite*=Syenite proper, composed essentially of orthoclase and hornblende (fig. 138).

(b) *Mica-syenite*, in which biotite more or less replaces the hornblende.
(c) *Augite-syenite*, an ordinary syenite in which augite is present.
(d) *Alkali-syenites*.—These are syenites distinguished by the presence of nepheline or sodalite.

Plagioclase is present as an accessory constituent in all syenites. When it becomes a prominent associate of the orthoclase, we get types that show a relationship to the diorites. To this intermediate type the name *monzonite* has been applied.

Syenites containing quartz form a connecting link with the hornblende granites.

Diorites.[1]—These are holocrystalline rocks of fine or fairly coarse texture. They consist essentially of plagioclase and hornblende. Free quartz is frequently present in them, but the influence of the basic felspar, oligoclase, or sometimes labradorite keeps the rock in the intermediate group.

The diorites generally occur as bosses or as dykes, and they are found in all parts of the globe. The leading types are as under—
(a) *Diorite*=plagioclase+hornblende.
(b) *Mica-diorite*=plagioclase+hornblende+biotite.
(c) *Quartz-mica-diorite*=plagioclase+hornblende+biotite+quartz.

Basic Plutonics.

Gabbro[2] **Type.**—These occur as dykes and large boss-like intrusions. They show a close relationship to the last group, and may be called *pyroxene-diorites*. They consist essentially of a plagioclase felspar (usually labradorite) and a pyroxene. When the pyroxene is augite or diallage, we get *gabbro* proper, and when hypersthene, *norite*.

Almost all the rocks of this group contain *olivine*, and in the more basic varieties it becomes an essential constituent.

Gabbro=plagioclase+augite or diallage.
Norite[3]=plagioclase+hypersthene.

When quartz is present, the rock becomes a quartz-gabbro or quartz-norite.

Many of the basic gabbros are rich in magnetite and ilmenite, and some pass into *iron-ore* rocks, as in Minnesota.

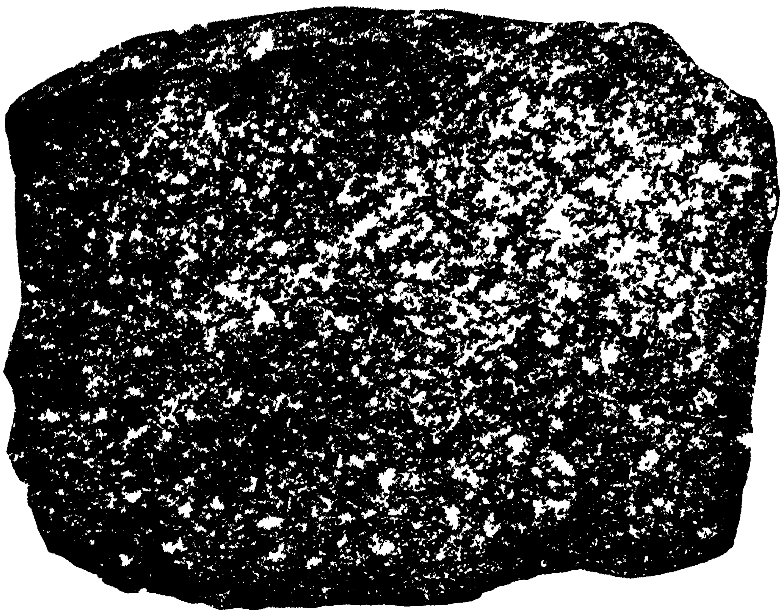
Ultra-Basic Plutonics.

Peridotites.[4]—These occur mostly as dykes in other basic rocks. They are holocrystalline in texture, and basic or ultra-basic in composition. They consist essentially of olivine, which may constitute 50 per cent. or more of the rock, while felspar is typically absent. Enstatite or bronzite is nearly always present and, in some types, augite or hornblende. The leading types are—

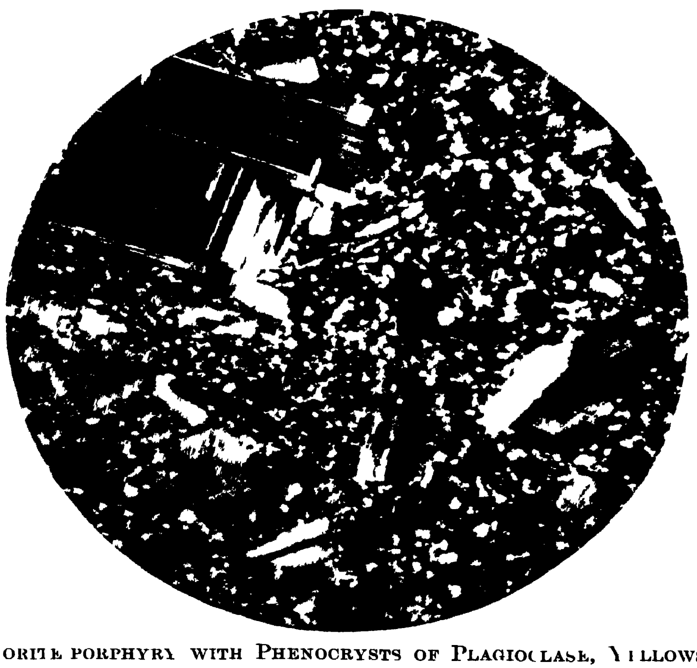
(a) *Enstatite-peridotite*=olivine+enstatite.
(b) *Augite-peridotite*=olivine+augite.
(c) *Hornblende-peridotite*=olivine+hornblende.

An olivine-rock containing a little chromite and magnetite forms mountain masses of great extent in New Zealand. It has received the distinctive name *Dunite*, so called after Dun Mt., where it is typically developed.

[1] Gr. *diorizo*=I distinguish.
[2] An Italian popular name used for these rocks in the neighbourhood of Florence.
[3] Nor (norv.)=north. The name was given first to some rocks occurring in the north of Scandinavia.
[4] Peridot=olivine.



A DIORITE, YELLOWSTONE NATIONAL PARK (U S Geol Survey)



B DIORITE PORPHYRY WITH PHENOCRYSTS OF PLAGIOCLASE, YELLOWSTONE NATIONAL PARK (After Iddings, U.S Geol Survey)

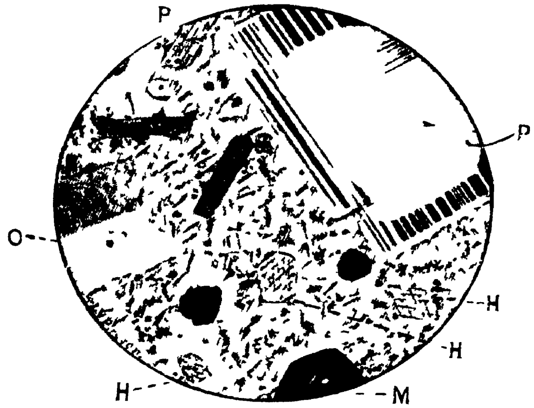


FIG. 139.—Micro drawing of diorite porphyry, U. S. Geol. Surv. (After Pirsson.)

P, Phenocryst of plagioclase with well developed albite-twinning and distinct pericline twinning.
O, Orthoclase. H, Hornblende. M, Magnetite.

FIG. 140.—Showing gabbro from Yellowstone National Park. (After Iddings.)

The olivine of the peridotites and dunite alters readily into the hydrous form, *serpentine.* Many serpentines are probably altered ultra-basic magmas.

B.—Hypabyssal Rocks.

The igneous rocks included in this group as a rule occur in the form of dykes, and are probably protrusions or apophyses from deep-seated bosses.

Most of them are holocrystalline, and this texture is so general as to be characteristic. In some, however, there is a glassy residue.

Dyke rocks, like the plutonics, are typically compact, but a few are known that possess a vesicular structure like a volcanic lava.

FIG. 141.—Micro-drawing of peridotite, deeply serpentinised. ×70. (After Hartog.)

O, Olivine. S, Serpentine apparently massive.
A, Antigorite, scale serpentine. G, Garnet.
Solid black, magnetite.

In some of the families of this group, the porphyritic structure is so constant as to be characteristic.

I. *Quartz-porphyry*—Acidic.
II. *Porphyries*, *Porphyrites*—Intermediate.
III. *Lamprophyres*, *Dolerite*—Basic.

ACIDIC GROUP.

Quartz-Porphyries.—These are also known as *felsites, quartz-felsites,* or *elvans.* They abound as dykes and veins in the neighbourhood of granite bosses, with which they are doubtless genetically related. Their colour varies from white to buff.

In the rocks of this family the ground-mass consists of a micro-crystalline or crystalline aggregate of quartz and felspar, in which are embedded crystals of quartz and orthoclase, and frequently biotite or some other ferro-magnesian mineral. Mineralogically and chemically many of the varieties of this family are merely fine-grained granites or *microgranites,* as they are sometimes called.

When the ground-mass is so fine that it is difficult to recognise the various constituents even under high powers, the rock is said to be *felsitic.*

The fine-grained and compact forms of granite frequently found traversing ordinary granites as narrow dykes, are called *quartz-felsite* in England, *micro-granulite* or *microgranite* in Continental Europe, and are covered by the name *eurite.*

The fine-grained granites that consist only of quartz and orthoclase in a felsitic ground-mass, are sometimes called *palite.*

Many of the so-called *felsites* and *quartz-felsites* are ancient rhyolites that have undergone some secondary changes.

Intermediate Group.

These are holocrystalline dyke rocks with a porphyritic structure, due in most cases to the presence of felspar phenocrysts. They are divided into two families, the *porphyries* and *porphyrites*; [1] the former is dominated with orthoclase, the latter with plagioclase. Thus, while the porphyries are related to the syenites, the porphyrites approach the diorites.

Porphyries.—The leading types of these are as follows:—

(*a*) *Orthoclase-porphyry*=orthoclase+a little biotite, hornblende, or augite.
(*b*) *Syenite-porphyry*=ground-mass of quartz and felspar, mostly orthoclase; phenocrysts, plagioclase+hornblende.

Porphyrites.—The leading types of these are—

(*a*) *Hornblende-porphyrite*=plagioclase+hornblende+biotite.
(*b*) *Mica-porphyrite*=plagioclase+biotite.

Basic Group.

Lamprophyres.—This is a peculiar family of basic, dark-coloured, dyke-rocks, typically found traversing rocks of older Palæozoic age. They are fine-grained and essentially holocrystalline. They are peculiarly rich in the ferro-magnesian minerals, biotite, hornblende, or augite. The felspars, which may be orthoclase or plagioclase, occupy a subordinate place. Olivine is absent or sparingly represented. In some the silica is as low as 40 per cent.

The various types take their name from the dominant ferro-magnesian mineral. Thus we have—

(*a*) *Hornblende-lamprophyre,* with dominant plagioclase=*camptonite* type.
(*b*) *Mica-lamprophyre.*
(*c*) *Augite-lamprophyre.*

In the monchiquitic [2] type of lamprophyre, the characteristic minerals are olivine+augite, or sometimes hornblende.

Dolerites.[3]—These occur as laccoliths, sills, and dykes. They are holocrystalline, but not conspicuously porphyritic. The leading types are as under—

(*a*) *Olivine-dolerite*=plagioclase+augite+olivine.
(*b*) *Mica-dolerite*=plagioclase+augite+biotite.
(*c*) *Hornblende-dolerite*=plagioclase+augite+hornblende.
(*d*) *Enstatite-dolerite*=plagioclase+augite+enstatite.

The more ancient dolerites have usually undergone considerable alteration to a greenish-black rock, to which the distinctive name *diabase* has been applied.

[1] Gr. *porphyra*=purple.
[2] From the Sierra de Monchique (Portugal).
[3] Gr. *doleros*=deceitful.

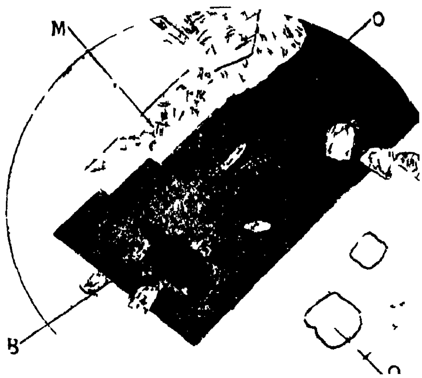


Fig. 142 — Micro drawing of quartz porphyry from Mariana Mine, Tres Cruces. Ground mass felsitic. (After Rumbold.)

O, Orthoclase. M, Felspar altered to muscovite.
B, Biotite. Q, Quartz.

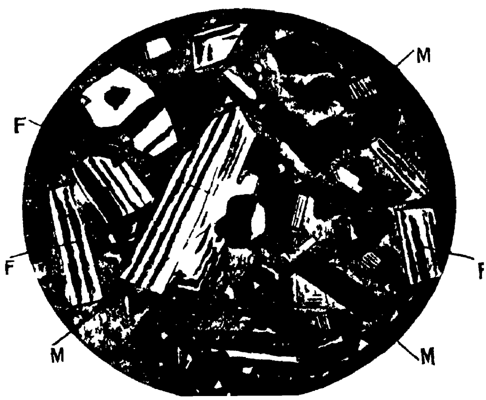


Fig. 144 — Micro drawing of Negro Pabellon mica andesite. (After Rumbold.)

Ground-mass, Glass. M, Mica altering to magnetite. F, Plagioclase felspar.

The greenish colour is due to the chloritic decomposition products. The principal varieties are—

(*a*) *Diabase* proper = plagioclase, mostly labradorite + augite.
(*b*) *Olivine-diabase* = plagioclase + augite + olivine.
(*c*) *Quartz-diabase* = plagioclase + augite + quartz.
(*d*) *Hornblende-diabase* = plagioclase + hornblende + augite unless uralised.

Many of the Palæozoic diabases are conspicuously amygdaloidal, notable examples being the copper-bearing diabases of Lake Superior, and the great sheet of diabase overlying the gold-bearing *banket* series of the Witwatersrand.

C.—Volcanic Rocks.

In this group are included all the solid effusive lavas as well as the dykes and sills that are directly connected with lava streams. They range from the

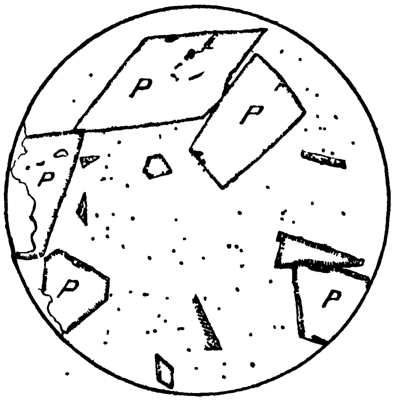


FIG. 143.—Showing phenocrysts of plagioclase (*P*) in glassy ground-mass, *U.S. Geol. Surv.*

glassy to the holocrystalline forms. The glassy structure is most prevalent among the acidic types of rock.

Volcanic rocks are frequently vesicular, and usually exhibit flow phenomena such as flow-lines, parallel orientation of crystals, elongation of bubble-vesicles, and banding. The majority exhibit a porphyritic structure, due to the presence of two generations of crystals. The large felspars separate out of the slowly uprising glassy magma, and, being free from crowding or interference, usually grow to a large size.

At a later stage of the eruption, probably after effusion of the magma as a lava-stream, the separation of the second crop of felspars begins ; and the rate of cooling being mo e rapid than before, the crystals are small and often crowded.

With the volcanic rocks, as with the plutonic and hypabyssal, we have the threefold division, based on chemical composition as under—

$$\begin{array}{ll} \text{I.} & \textit{Rhyolites} \text{ — Acidic.} \\ \text{II.} & \left\{ \begin{array}{l} \textit{Trachytes} \\ \textit{Phonolites} \\ \textit{Andesites} \end{array} \right\} \text{Intermediate.} \\ \text{III.} & \textit{Basalts} \text{ — Basic.} \end{array}$$

Acidic Group.

Rhyolites.—These include all the more acid lavas of Recent and Tertiary date, as well as the contemporaneous lavas and dykes associated with the Palæozoic and Mesozoic formations, which generally have assumed the type of quartz-porphyries.

The ground-mass may be wholly or partly glass, or crypto-crystalline. Fluxion structure is usually well marked by alternating bands of different texture and colour, or by alternating glassy and spherulitic layers. The vitreous or glassy form is found in *obsidian*, which is a natural volcanic glass in which crystallites or embryonic crystals are frequently developed.

The phenocrysts of rhyolites are orthoclase, including the glassy form sanidine, an acidic plagioclase, quartz, biotite, and sometimes augite or hornblende.

Tertiary rhyolites are found in Antrim, in the Lipari group of islands, Nevada, and New Zealand ; and recent rhyolites in New Zealand.

Intermediate Group.

Trachytes.[1]—These are in some respects rhyolites without free quartz. The sanidine form of orthoclase is the chief constituent of the ground-mass and also the dominant phenocryst. Hornblende or biotite is nearly always present in true trachytes.

Phonolites.[2]—These rocks are distinguished by the presence of *nepheline* in the ground-mass. Those poor in that alkali-mineral are closely related to the trachytes. The varieties in which nepheline is fairly abundant are sometimes called *nephelinitoid phonolites*.

Andesites.[3]—In most typical andesites the ground-mass is a felted mass of felspar laths, and a residue of glassy matter. The phenocrysts are plagioclase, hornblende, augite, biotite, or hypersthene.

The different varieties of andesite are named from the dominant ferro-magnesian mineral, thus—

(*a*) *Augite-andesite.*
(*b*) *Hypersthene-andesite.*
(*c*) *Hornblende-andesite.*
(*d*) *Quartz-andesite* or *dacite.*
(*e*) *Mica-andesite.*

Among the accessory minerals, magnetite, ilmenite, apatite, and zircon are usually present.

The andesites that have been altered by thermal waters, steam, or gases are sometimes called *propylite.*

The andesites of United States, New Zealand, and Transylvania are of great importance for their valuable gold- and silver-bearing lodes.

Basic Group.

Basalts.—These occur as lavas, sills, and dykes. The essential minerals are a plagioclase felspar, rich in lime, augite, and olivine. They exhibit every form of texture from the glassy to the holocrystalline.

In the glassy form we have *tachylyte* ; and in those basalts in which the

[1] Gr. *trachys*=rough.
[2] Gr. *phone*=voice ; for phonolites, when struck, give a singing sound.
[3] So named from the Andes in South America.

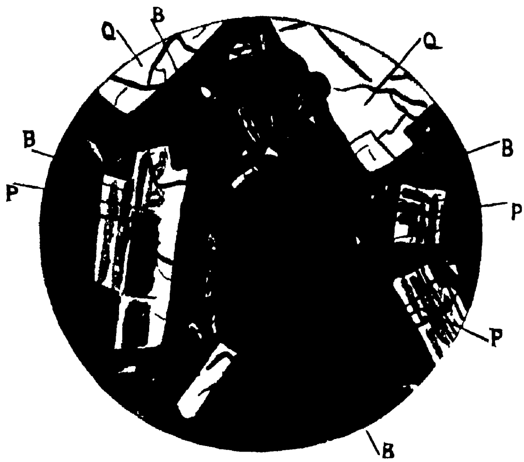


FIG. 145.—Micro drawing of biotite dacite from Huanuni. (After Rumbold.)

Ground-mass, Glass. B, Biotite. P, Plagioclase. Q, Quartz.

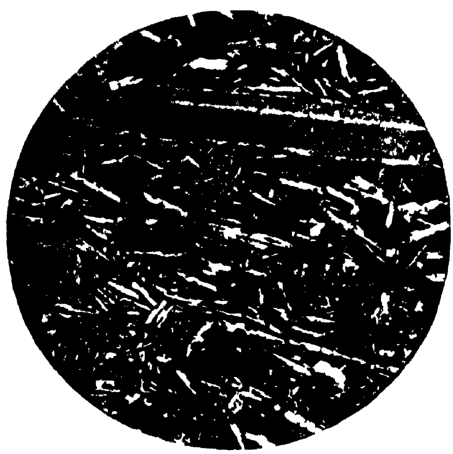


FIG. 146.—Microphotograph of olivine-basalt from North Auckland, N.Z., showing phenocryst of plagioclase and ophitic structure of ground-mass; there is a general orientation of felspars.

phenocrysts are embedded in a holocrystalline ground-mass we get rocks that are essentially dolerites.

The typical rock of this group is *olivine-basalt.*

Melaphyr is a basalt of older formations, this special name having been introduced in a time when rocks of different age were called with different names. The name has now been discarded by British geologists.

SUMMARY.

1. Plutonic rocks occur in boss-like masses that have been uncovered by denudation.

2. They are holocrystalline in structure, and evidently cooled slowly and under great pressure.

3. The order of crystallisation in plutonic rocks is one of *decreasing basicity*; that is, the basic minerals separate out first, and the acid last.

4. The leading type of the acidic plutonics is *Granite*; of the intermediate plutonics, *Syenite* and *Diorite*; of the basic, *Gabbro* and *Norite*; and of the ultra-basic, *Peridotite.*

5. Hypabyssal igneous rocks occur mostly as dykes, and their texture is usually holocrystalline. The acidic types are closely related to the granites, and the intermediate to the syenites and diorites. Some of the intermediate families are characteristically porphyritic.

6. The volcanic rocks include all the solid lavas and the dykes that are directly connected with lava streams. They range from the glassy to the holocrystalline forms of texture.

The rhyolites are typical of the acidic group, the andesites of the intermediate, and the basalts of the basic.

CHAPTER XVIII.

METAMORPHISM AND METAMORPHIC ROCKS.

Metamorphism.

METAMORPHISM [1] means the reconstruction of rock-masses by the action of water under varying conditions of temperature and stress, and must not be confused with the alteration of rocks by the ordinary processes of weathering, nor with the changes effected by hydration.

Rocks, in the zone of weathering, may be altered by oxidation and hydration; or a rock may be completely altered by hydration alone; but these changes, though usually referred to as "rock-alteration," bear no relationship to metamorphism, which is mass-alteration of a peculiarly distinctive type.

In metamorphic rocks the original constituents of the rocks have in many cases formed new combinations among themselves. The minerals developed by this process of alteration invariably possess a crystalline structure; hence metamorphic rocks are frequently spoken of as *crystalline*. In many metamorphic rocks, the newly developed minerals have arranged or aggregated themselves in more or less parallel layers or *folia* that give rise to the structure called *foliated*. Foliation is characteristic of many metamorphic rocks. Foliated rocks usually split readily into thin plates or flags parallel with the foliation planes. Metamorphic rocks that split in this way are called *schists*.[2]

Genesis of Metamorphism.—The three agencies chiefly concerned in the metamorphism of rock-masses are *heat*, *pressure*, and *water*.

The heat and pressure may arise from three possible sources, namely—igneous intrusions, the intense folding of strata, or the subsidence of crustal blocks within the zone of high subterranean temperatures.

The water may be magmatic, or interstitial in the sedimentary rocks subjected to heat and pressure.

According to the source of the heat, the alteration of rock-masses may be divided into—

(1) *Contact-Metamorphism.*
(2) *Regional Metamorphism.*

This classification is partly genetic and partly morphological, and hence not entirely satisfactory. When we use the term Contact-Metamorphism as meaning that an uprising magma has altered the rock with which it comes in contact, it is clearly implied that the expression has a genetic significance. On the other hand, Regional Metamorphism is merely a geographical expression. To obtain geographical consistency metamorphism should be grouped as—

(1) Local Metamorphism.
(2) Regional Metamorphism.

[1] Gr. *meta*=change, and *morphe*=shape. [2] Gr. *schistos*=easily split.

Metamorphism is the result of physio-chemical processes, and the principal agent concerned in the reactions is water or water-vapour. Chemical activity is known to be greatest at high temperatures and pressures, hence it is generally assumed that rock-metamorphism took place at high temperatures and under great pressure. But it must always be borne in mind that water in a long interval of time may effect, even at low temperature and moderate pressure, greater changes in a rock-mass than an intrusive magma with its high temperature can accomplish in a relatively short time.

Genetically considered, metamorphism, according to the agents supposed to have originated the rock-alteration, may be divided into—

(1) Contact or Hydro-pneumatolytic Metamorphism.
(2) Dynamic Metamorphism arising from shearing and folding stress.

The scope of Contact-Metamorphism is narrow, and clearly confined to the rocks in the vicinity of a magmatic intrusion. But the subdivision "Dynamic Metamorphism" is not sufficiently comprehensive to cover all that Regional Metamorphism implies. Intense folding does not always produce rock-metamorphism; and a high degree of metamorphism may be found in formations that show little or no evidence of disturbance.

Great thicknesses of the pre-Cambrian Algonkian system of Canada, consisting of conglomerates, sandstones, and shales, though acutely folded and deeply involved, are practically unaltered, as also are the sheared Torridonian sandstones, shales, and grits of Scotland. On the other hand we find, in Central Otago,[1] a thickness of over 8000 feet of highly altered mica-schist lying nearly horizontal over an area of 30,000 square miles. The metamorphism of the Otago schists is regional, but unrelated to orogenic movement. But it should be noted that in these mountain-chains of alpine type horizontality of strata does not prove the absence of folding.

There are metamorphic rocks of all ages, but generally the rocks of the greatest antiquity are the most altered.

Till we possess a better understanding of the origin of rock-metamorphism, the subject will be discussed under the terms Contact-Metamorphism and Regional Metamorphism.

Contact-Metamorphism.—All igneous intrusions produce a certain amount of alteration in the rocks which they invade. In the case of lavas the thermal effects are, as a rule, slight and unimportant. Moreover, the alteration caused by the intrusion of small dykes and thin sills is in most cases remarkably small, and is generally confined to the dehydration and baking of the skin of rock at the actual line of contact. Coals, however, may be changed to anthracite, or even graphite; and pieces of clay entangled in the magma baked into an impure porcelain called *porcellanite*.

Large dykes and plutonic bosses that have cooled slowly and under pressure, frequently effect considerable changes in the rocks into which they intrude. Along the line of contact, the intruded rocks are usually baked and hardened, but as a rule the mere thermal effects of dry heat are among the least conspicuous of the changes effected by the intrusion. In some cases the invaded rock is shattered and impregnated with new minerals for many hundreds or even thousands of yards beyond the actual contact; in other cases it is metamorphosed into a foliated crystalline schist.

The metamorphic effect of great plutonic intrusions is mainly hydrothermal, and hence is greatest at the contact, gradually diminishing as the

[1] J. Park, "The Geology of Alexandra District, Central Otago," *Bull. 2, N.Z. Geol. Surv.*, Wellington, 1906.

distance from the intruding mass increases. The amount of change arising from *contact-action* will depend on the degree of heat, rate of cooling of the igneous mass, the thickness of the superincumbent strata, as well as on the chemical composition and structure of the invaded rocks.

The dominant sedimentary rocks in the rocky crust are sandstones, shales, and limestones. Sandstones are changed into quartzites, the shales into slate or mica-schist, and the limestones into marbles. Banded sandstones and clayey beds become changed into gneiss; and an argillaceous sandstone may be altered into a crystalline rock that can be distinguished from an intrusive granite only by the chemical analysis.

Pressure alone will alter argillites and shales into true slates possessing the characteristic *slaty cleavage*, but heat, pressure, and water acting together will usually lead to the development of sericite mica on a grand scale. In the zone of greatest pressure, the shale may be changed completely into mica, forming a phyllite; or in cases where the shale is sandy, into mica-schist or even gneiss.

The mechanical stress arising from intense folding favours the production of many secondary minerals, among them sericite and chlorites, of albite among the felspars, of amphiboles as opposed to pyroxenes, of talc, rutile, and cyanite.

Where an igneous dyke has intruded slates there is frequently developed in the slate a crop of what are called *contact minerals*. These secondary crystalline minerals are mostly simple silicates of alumina, and the commonest are *chiastolite* and *andalusite*. When the intruded rock contains sufficient lime and alkali to combine with the free silica many complete silicates may be developed, conspicuously *micas* and *amphiboles*.

Pure limestones are changed to granular marbles, while impure limestones give rise to a series of complex lime-silicates, of which *grossularite* (lime-garnet), *actinolite*, *wollastonite*, and *diopside* (lime-pyroxenels) are the most common.

The mere fact that a series of sedimentary rocks becomes more and more altered as a granitic boss is approached does not, of itself, afford conclusive proof that the granite is intrusive in the sedimentary formation. Many granitic massifs are fixed blocks of great antiquity, against which younger formations have been crushed and intensely folded, and in the process have suffered a high degree of metamorphism. Hence when an altered sedimentary formation lies against a granite boss, it is not safe, in the absence of *apophyses* [1] or intrusive veins on the fringe of the igneous mass, to conclude that the granite is younger than the altered clastic rocks with which it is in contact.

The slower the magma cools, the greater are the changes effected by it. Hence we usually find that the greatest alteration has been effected by granites, diorites, and other plutonic masses of coarse texture.

Among the non-metallic minerals introduced into or developed in the country-rock by the igneous intrusion are biotite, tourmaline, hornblende, epidote, felspars, garnets, and idocrase; and of metallic minerals, ores of tin, wolfram, copper, gold, silver, and iron. The impregnation of the country-rock within the aureole or zone of metamorphism with tin and wolfram is a characteristic feature of granite intrusions.

Obviously such extensive alteration and impregnation must be due to some other agency than mere dry heat alone.

Daubrée's experiments on silicates and rocks have shown that not dry heat alone, nor even vapours or gases, would be sufficient to effect changes of any moment; but that superheated water, under great pressure, was the most important agent concerned in metamorphism. To prove this he partially filled

[1] Gr. *apophusis*=an offshoot.

a glass-tube with water, sealed both ends, and placed it in a strong iron tube which was closed, and exposed to a temperature below red heat for several days. The glass tube was attacked by the water and converted into a zeolitic mineral. In some places a laminated, in others a spherulitic, structure was developed. With superheated steam he obtained orthoclase and a micaceous mineral.

During the process of cooling, the intrusive magma will probably liberate enormous quantities of steam, which will penetrate the surrounding rocks for considerable distances. At a certain point the steam will be condensed into superheated water, which will continue the work of metamorphism in the outer zone of the aureole. When the igneous mass and the neighbouring country-rock have sufficiently cooled, the zone of steam and vapour surrounding the boss will

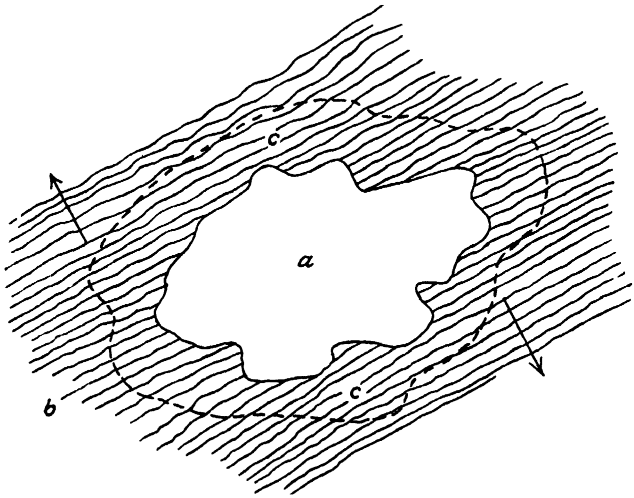


FIG. 147.—Showing aureole or zone of metamorphism, N.S.W.

(a) Granite boss. (b) Mica-schist. (c) Zone of tin impregnation.
The arrows mark the dip of the schists.

be invaded by superheated water, and in this way we may get the metamorphic effects of the vapour and gases supplemented by those of superheated water.

The intrusion of an igneous magma is thus capable of performing an important rôle in the process of metamorphism and mineralisation. By its intrusion it cracks and fissures the surrounding rocks. It is a source of great heat, which is slowly transferred to the country-rock ; and is a carrier of steam and gases, which are capable of altering the constitution of the surrounding rocks, and impregnating them with mineral matter, perhaps mainly derived from the parent magma.

Regional Metamorphism.—Foliated crystalline rocks frequently cover thousands of square miles in regions where they have no direct association with known plutonic intrusions. And, singularly enough, these rocks for thousands of square miles, and sometimes throughout an enormous thickness, may exhibit as high a degree of metamorphism as the most intense alteration produced on the borders of a great plutonic boss.

The origin of this widespread regional metamorphism is not well understood. By some it is believed to have been caused by the uprising of enormous floods of plutonic magmas that consolidated at a considerable depth and have never been uncovered by denudation. In other words, this view supposes that

regional metamorphism is merely an exaggerated kind of contact-metamorphism.

Another hypothesis postulates that great crustal blocks lying under piles of younger strata have been depressed by subsidence till brought within the influence of a high subterranean temperature. This view is merely a modification of the Huttonian plutonic theory, according to which blocks of rock were depressed till they reached a zone where they were first softened and melted, eventually crystallising as they cooled.

The temperature of the Earth increases with increasing depth below the surface, but is not proportional to the depth. In volcanic regions the zone of high temperature lies close to the surface, but in non-volcanic regions the temperature-gradient varies enormously. In some regions the rate of increase of temperature is as high as 1° Fahr. for every 60 feet of depth ; in other places it is not more than 1° Fahr. in 200 or more feet. Moreover, the rate of increase of temperature is not uniform. But it is not unreasonable to suppose that with considerable subsidence and a thick covering of strata a sufficient heat might be encountered at a depth of a few miles to effect in the presence of superheated water great alterations in the constitution of rock-masses, without actual softening and fusion, as required by the Huttonian theory.

The intensity of metamorphism of rocks is in many cases, perhaps the majority, proportional to the amount of crushing, folding, and plication they have suffered. The metamorphism induced by intense folding and other crustal movements constitutes what is sometimes called *dynamic metamorphism*. In this case we are warranted in assuming that the heat and pressure of crustal movement in conjunction with water were important, but not necessarily the sole, agents of metamorphism. For it is obvious that the powerful lateral or tangential stresses generated by crustal movement, can only become effective in the production of intense folding and plication when they are strongly resisted by the vertical stress of a pile of superincumbent strata. The existence of such a pile of strata would necessarily imply considerable subsidence, sufficient perhaps to bring the basement rocks within the influence of a high subterranean temperature, not sufficiently high to cause fusion, but enough to supplement the heat generated by the folding.

But intensely folded strata are not always altered into metamorphic rocks. On the contrary, they frequently exhibit little or no evidence of internal change. And crystalline schists are not always folded. The highly altered mica-schists of Central Otago in New Zealand lie perfectly horizontal, or are gently undulating, over thousands of square miles, and they are not connected with any visible plutonic masses.

The genesis of regional metamorphism is a difficult problem for which no satisfactory solution has been formulated. When we review the available evidence, it does not seem unwarrantable to assume that regional metamorphism may be caused partly by folding and partly by the subsidence of crustal blocks till they come within the zone of considerable subterranean heat.

Metamorphic Rocks.

Metamorphic rocks may be *schistose* or *massive*. In the schistose group, the original matter has become for the most part crystalline, and a *foliated* or schistose structure has been induced by the arrangement of the newly formed crystalline constituents in short leaves or *folia* [1] lying more or less parallel with one another.

[1] Lat. *folia*=leaves.

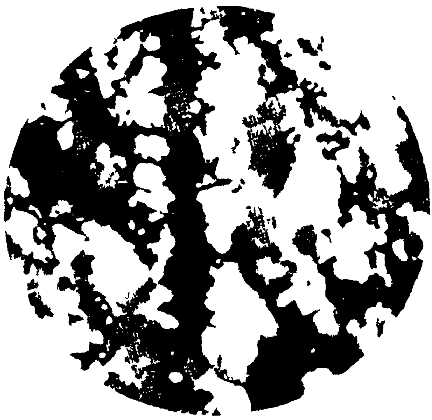


FIG. 148.—Photomicrograph of quartz biotite schist from Central Otago, N.Z.

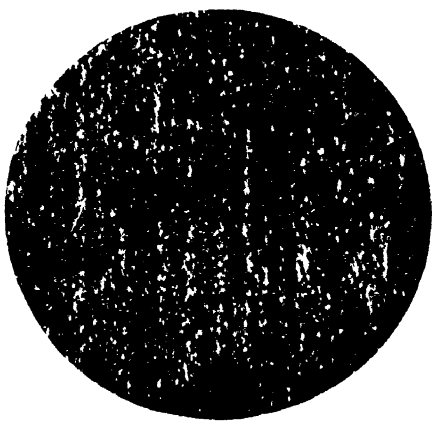


FIG. 149.—Photomicrograph of phyllite from Central Otago, N.Z.

The separate folia may consist of one or several minerals. They usually occur as flat lenses, sometimes even and parallel, but most frequently overlapping, uneven, and undulating, puckered, or plicated. In many of the more highly altered rocks they thin out rapidly in all directions, again increase in size, and once more thin out, and so on indefinitely.

The folia may vary from a fraction of an inch to several inches or even many feet thick. Fossils present in the original sediments are usually completely obliterated by the development of the crystalline structure.

The foliation planes may be parallel to the original bedding planes or they may follow any direction. The foliation is doubtless developed in the rock when under the influence of enormous pressure; and it is not improbable that the foliation planes, like slaty-cleavage to which they are closely related, always lie at right angles to the direction of the stress.

Rocks are found showing all degrees of metamorphism from highly contorted granitoid gneissic schists to altered sediments in which the character of the original sediments can still be traced.

Many of the older schists are believed to be altered igneous rocks of great antiquity. The greenstones (altered andesites and basalts) forming the hanging-wall of the Alaska-Treadwell ore-body on Douglas Island, Alaska, possess a well-developed schistose structure, as also do some of the greenstones or amphibolites associated with the gold-bearing lode-formations at Kalgoorlie.

Among the massive metamorphic rocks that possess a crystalline structure, but are not foliated, are marble and quartzite.

Foliated Schists.

The leading and most prevalent types of these rocks are as follows:—

Gneiss is a schistose aggregate of quartz, felspar, and mica (muscovite or biotite). Accessory minerals: usually hornblende, magnetite, garnet, rutile, tourmaline, and pyrite. Abundant in Canada, Highlands of Scotland, Scandinavia, and New Zealand. Usually a rock of great antiquity. It may graduate into mica-schist on the one hand, or become granitoid on the other.

The different varieties of gneiss are named after the dominant ferro-magnesian mineral.

Mica-Schist consists of alternating folia of mica (mostly muscovite) and quartz. Accessory minerals: magnetite, garnet, rutile, and pyrite. Abundant in Canada, Highlands of Scotland, Scandinavia, Alps, New South Wales, Western Australia, and New Zealand.

Chlorite-Schist is a schistose aggregate of scaly chlorite. Accessory minerals: magnetite, specular iron, felspar, talc, epidote, mica, actinolite, and apatite. Commonly occurs as subordinate bands in mica-schist. In many cases appears to be a metamorphosed basic igneous rock. The characteristic colour is a pale olive green.

Hornblende-Schist is usually an aggregate of hornblende, quartz, felspar, and mica. Accessory minerals: magnetite, garnet, and epidote. This schist is probably an altered igneous rock. It commonly occurs in association with gneiss and mica-schist.

Actinolite-Schist, composed mainly of light- or dark-green actinolite, often in clustering or radiating sheaves, is a common associate of mica-schist and gneiss.

Quartz-Schist is a flaggy quartzite that breaks readily into thin laminæ. Sometimes the splitting is facilitated by the presence of mica along

the foliation planes. In this case we get a *micaceous quartz-schist*, which may graduate into an ordinary mica-schist. The common accessory minerals are actinolite, garnet, specular iron, and magnetite. Quartz-schist forms bands associated with mica-schist and slate in the older Palæozoic formations. Found in all the continents.

Talc-Schist consists of scaly talc, often with some quartz, chlorite, or mica. Colour pale-green or grenish-grey. Feels greasy and is quite soft. Accessory minerals: magnetite, tourmaline, felspar, magnesite, and actinolite. Frequently associated with mica-schist as small subordinate bands.

Phyllite, a highly altered clay-shale in which an abundance of mica has been developed. When the mica forms the dominant constituent, the rock possesses a silvery-grey colour and a silky lustre. Quartz is frequently present. Phyllite is intermediate between an ordinary clay-slate and mica-schist, into either of which it may pass insensibly.

Clay-Slate is a compact finely-granular clay-rock. Splits readily into thin plates in a direction parallel with the slaty-cleavage, which may coincide with the original planes of deposition, or lie in any other direction. The colour ranges from grey to green, blue, and purple. Clay-slate is essentially composed of hydrous silicate of alumina and various other silicates. The accessory minerals are quartz, mica, felspar, rutile, iron oxides, and pyrite. *Graphite-slate* contains a large amount of graphite. *Spotted-slate* is a slate containing little knots or spots which would appear in some cases to be incipient forms of *chiastolite* or *andalusite*. These minerals are frequently developed in slates near igneous contacts, and when relatively abundant give rise to the varieties of slate called *chiastolite-slate* or *andalusite-slate*.

As a rule, the schistose structure is best developed in fine-grained rocks, but under the influence of great pressure even conglomerates may become schistose.

Massive Crystalline Rocks.

Marble is a granular crystalline aggregate of calcite of fairly uniform texture. The accessory minerals may be mica (generally muscovite), talc (or more rarely graphite scales), garnet, actinolite, tremolite, or molybdenite scales. A marble is merely a metamorphosed limestone; and when the original limestone was pure we get a high-class marble, and when impure a low-grade marble, the impurities being changed into the accessory minerals.

Quartzite is a rock consisting essentially of quartz grains cemented with silica. It is an altered sandstone and possesses a crystalline texture induced by heat in the presence of water. The grains frequently present a semi-fused appearance. Quartzite can be formed from blocks of sandstone subjected to prolonged heat. The metamorphism is probably accelerated by the presence of superheated water. Where igneous rocks have intruded into sandstones, a zone of the latter surrounding the intrusive mass is frequently altered into typical quartzite.

Serpentinisation.—Serpentine is a hydrous mineral of secondary origin resulting from the alteration of ferro-magnesian minerals, as olivine, augite, and hornblende, especially the former.

Chemically considered, serpentine is essentially a hydrous silicate of magnesia. But most serpentines contain a small but variable proportion

of silicate of iron and silicate of alumina, the amount depending on the composition and degree of alteration of the original mineral.

Serpentinisation is probably brought about by the action of heated waters and aqueous vapours.

Serpentine may occur as grains in altered basic rocks, or as a serpentine rock where ultra-basic rocks, as peridotite or dunite, have been altered. An aureole of massive serpentine frequently surrounds sheets or dykes of dunite and olivine, but in many cases the original rock has been completely serpentinised.

Serpentine-schist, mostly as thin bands and lenses, often occur in association with metamorphic rocks as the alteration product of ultra-basic igneous rocks. Other serpentine-schists pass insensibly into ordinary schists, the serpentinous matter having apparently been deposited by percolating waters.

Many crystalline limestones are closely veined with serpentinous matter, the origin of which is obscure. The original calcareous sediments may have contained silica, magnesia, iron, and alumina that, in the process of rearrangement, crystallised as ferro-magnesian minerals. Secondary minerals are common in some limestones, among them micas, amphiboles, wollastonite, grossularite, and diopside.[1]

SUMMARY.

(1) Metamorphic rocks usually possess a more or less crystalline structure. They may be foliated or massive. In the foliated rocks the constituents are arranged in approximately parallel or overlapping lenses. The foliated rocks split readily along the foliation-planes; and are therefore called schistose.

(2) The massive metamorphic rocks are marble and quartzite.

(3) The most abundant crystalline schists are gneiss, mica-schist, chlorite-schist, quartz-schist, and phyllite.

(4) The alteration or metamorphism of rocks is mainly due to heat, pressure, and superheated water.

(5) The metamorphism may be what is called *contact-metamorphism*, which is caused by igneous intrusions and hence quite local; or *regional metamorphism*, which affects large areas of rock.

(6) The effects of contact-metamorphism have been successfully imitated by Daubrée and others on artificial compounds.

(7) The origin of regional metamorphism is still obscure. It may be due (*a*) to the uprising of floods of plutonic magmas that have consolidated at a considerable depth and have never been exposed by denudation; (*b*) to the subsidence of large crustal blocks to the zone of subterranean heat; or (*c*) to the intense folding and plication of rocks subjected to the load of a pile of superincumbent strata.

It is not improbable that in certain situations, one, two, or all of these together, may have been concerned in the process of metamorphism.

(8) Serpentinisation refers to the alteration of olivine and the minerals of the pyroxene and amphibole (hornblende) groups. Serpentine itself is a hydrous silicate of magnesia with usually a small but variable amount of iron, and an even smaller proportion of alumina. It may occur in grains in altered igneous rocks or in rock-masses. Serpentinisation is probably brought about by heated waters or aqueous vapours, and may be partly pneumatolytic. Many ancient limestones are serpentinous.

[1] For discussion on the origin of Serpentine see "The Origin of Serpentine—a Historical and Comparative Study," by Prof. W. N. Benson, *Am. Jour. Sci.*, Dec. 1918, pp. 693–731.

CHAPTER XIX.

FOSSILS: THEIR OCCURRENCE, PRESERVATION, CLASSIFICATION, AND USES.

THE remains of animals and plants that have been embedded in rocks, as well as all traces, casts, impressions, and trails of what were at one time living organisms, are called fossils.

Fossils are found in the majority of stratified rocks; and since most stratified rocks are of marine origin, it is not surprising to find that the majority of fossils belong to organisms that lived in the sea.

The most abundant fossils are the shells of marine molluscs; and after these come corals and foraminifera.

Preservation of Fossils.—Let us consider the case of the molluscs. Most molluscs are provided with a calcareous shell or covering. When the animal dies and the soft parts decay, the shell usually becomes filled up with sand or mud, and is eventually buried in the sediments that are continually accumulating on the sea-floor.

Shells buried in a mud or fine sediment that subsequently becomes hardened into an impervious rock are usually perfectly preserved, with the exception perhaps of the original colouring. But shells embedded in a sandstone through which water can percolate freely are frequently dissolved and removed by the water, and there remain only *external casts*, or impressions of the *exterior* of the shells (fig. 150, *a*). In cases where the shell was filled with sediment at the time it was buried, besides the external mould, there will be found, when the shell is dissolved, an *internal cast* reproducing the exact shape of the *interior* of the shell (fig. 150, *b*).

By filling with plaster the space from which the shell was dissolved a *hollow cast* is obtained that is in all respects a replica of the original shell. If, on the other hand, we remove the internal cast, and fill the whole interior of the mould or impression from which it was removed with plaster, we shall get a solid representation of the outward form of the shell before its burial.

When a shell is gradually replaced by mineral matter deposited from water percolating through the rock, we frequently get a complete reproduction of the whole organism even to the minutest detail. The carbonate of lime of the shell may be replaced by carbonate of iron, pyrite, or silica. Siliceous replacements of bones and wood are quite common, and often they preserve the internal structure with marvellous exactness.

Shells that live in sand or mud become buried, as a rule, in the place where they lived. But many shells are cast up on the beach, where they are broken up into sand by the pounding action of the waves. It is in this way that shelly sands are formed. The sands of coral islands are mainly composed of broken corals and calcareous algæ. Thick shells that are not easily comminuted soon become rounded and water-worn.

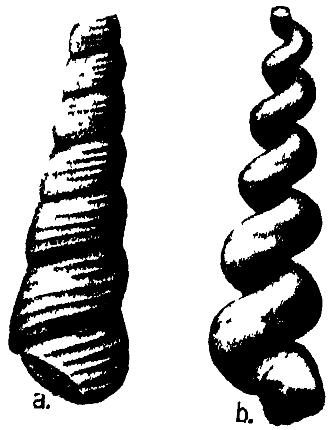


Fig. 150. Showing fossil casts of *Turritella*.
(*a*) Cast of exterior of shell. (*b*) Cast of interior.

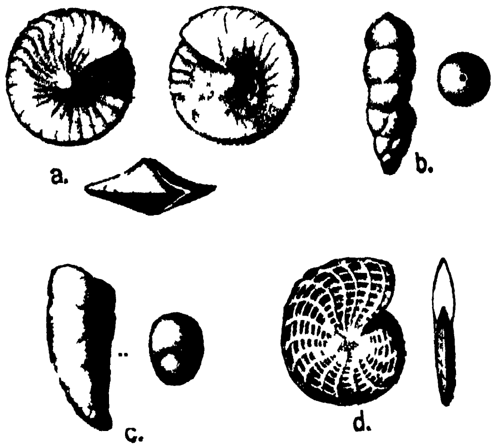


Fig. 151. Showing fossil foraminifera.
(*a*) *Amphistegina*. (*b*) *Clavulina*. (*c*) *Textularia*. (*d*) *Polystomella*.

The fossil shells that occur in rocks composed of littoral deposits are frequently fragmentary and water-worn.

Deltaic and estuarine deposits may contain the remains of land animals and plants, mingled with estuarine and marine forms.

Shelly limestones are usually composed of the dead shells of gregarious molluscs that grew on shell-banks ; and coral-limestones are formed where the coral-builders lived ; but deep-sea shells are not infrequently found in shallow-water deposits, and littoral shells in deep-sea sediments where they have been carried by sea-currents.

The remains of land animals and plants are sometimes carried far out to sea, where they become buried among marine organisms ; but marine deposits are typically distinguished by the presence of marine organisms, and terrestrial deposits by terrestrial organisms.

Fossiliferous Rocks.—As a rule the best-preserved fossils are found in rocks composed of fine sediments. Clays, marls, shales, and limestones frequently contain a rich and varied assemblage of fossils in a beautiful state of preservation.

The best leaf-impressions are met with in fissile shales and argillaceous sandstones, and they are most numerous where the rock is black and carbonaceous.

Coarse sandstones, grits, and conglomerates are characteristically poor in organic remains ; and when shells are present in them, they are usually broken and water-worn. In most sandstones the fossils are represented by *internal casts*, and impressions of the exterior of the shells or organisms.

Volcanic tuffs intercalated with marine strata are sometimes richly fossiliferous, but igneous rocks are devoid of all organic remains except those that occur in blocks derived from fossiliferous sedimentaries in the neighbourhood of the volcanic vent.

Derived Fossils are comparatively common in the pebbles and boulders of pebbly beds and conglomerates. Conglomerates, like all other sedimentary rocks, are composed of material derived from older rock-formations, many of which were fossiliferous. When a fossiliferous rock-formation becomes broken up by denudation some of the pebbles may contain fossils, and in this way the conglomerate, of which these pebbles eventually become a constituent, may contain *derived fossils*. A Tertiary conglomerate may contain Tertiary shells embedded in the sandy matrix, and derived fossils of Silurian age embedded in the pebbles. The fossils met with in the matrix are contemporaneous, and belong to molluscs that lived in the sea at the time pebbles and sands were deposited. But this requires some qualification. Derived fossils do not always occur embedded in pebbles or blocks. They are sometimes met with in sandy and clayey rocks mingled with the contemporaneous shells from which they cannot always be easily distinguished. In places were the sea-coast is fringed with low-sloping cliffs composed of fossiliferous sands, clays, marls, or shales, it sometimes happens that well-preserved shells become liberated by the crumbling away of the rock and fall on to the beach, where they become embedded in the sands or mud accumulating on the sea-floor.

Classification of Living Organisms.

All living organisms are divided into two kingdoms, namely—

I. Animal kingdom.
II. Vegetable kingdom.

The Animal Kingdom.

The study of the animals that now inhabit the globe belongs to the domain of the science known as *Zoology*. The branch of Zoology which concerns itself with fossil organisms is called *Palæontology*.[1]

For convenience of study, animal life has been subdivided into *Species*, *Genera*, *Families*, *Orders*, *Classes*, and *Sub-kingdoms*, in much the same way as the human race is divided into *Individuals*, *Families*, *Tribes*, *Nations*, and *Races*. Thus the related members of a household constitute a Family, a number of families form a Tribe or Clan, a number of tribes form a Nation, and several related nations constitute a Race.

The individuals of any kind of animal are called *species*; and a *species* may be defined as comprising those individuals that are the same in all essential features, and reproduce their kind true to the type.

A *genus* includes all the *species* that are nearly related by some prominent structural characteristic. Thus all the species of the cat-kind, whether domestic or wild, are included in the genus *Felis*. In this way we have—

Felis catus=the domestic cat.
Felis tigris=the tiger.
Felis leo =the lion.

Similarly all the members or species of the dog-kind are grouped in the genus *Canis*. Thus we have—

Canis familiaris=the domestic dog.
Canis lupus =the wolf.
Canis vulpes =the fox.

Related genera are grouped in *Families*, related families in *Orders*, related orders in *Classes*, and related classes in *Sub-kingdoms*, of which there are nine.

The groups of animals that are known to occur in the fossil state, beginning with the simplest forms and ending with the most highly organised, are as shown in the following table:—

OUTLINE CLASSIFICATION OF ANIMAL KINGDOM.

Sub-kingdoms.	Classes.	Fossil Types.
I. Protozoa	Rhizopoda.	Foraminifera, Radiolaria.
II. Porifera	Spongiæ.	Sponges.
III. Cœlenterata	(a) Hydrozoa.	Graptolites.
	) Actinozoa.	Coral-reef builders.
IV. Echinodermata	) Crinoidea.	Sea-lilies.
	) Asteroidea.	Starfishes.
	(c) Echinoidea.	Sea-urchins.
	) Blastoidea.	Occur only as fossils.
	(e) Cystoidea.	
V. Annulata	Annelida.	Worms.
VI. Molluscoidea	(a) Polyzoa.	Sea-mats.
	(b) Brachiopoda.	Lamp-shells.
VII. Mollusca	(a) Lamellibranchiata.	Oysters and common bivalves.
	(b) Gasteropoda.	Univalve shells.
	(c) Cephalopoda.	Nautilus, ammonites.

[1] Gr. *palaios*=ancient, *onta*=beings, and *logos*=a description or discourse.

Sub-kingdoms.	Classes.	Fossil Types.
VIII. Arthropoda	(a) Crustacea.	Crabs.
	(b) Arachnoidea.	Spiders, scorpions.
	(c) Insecta.	Insects.
IX. Vertebrata	(a) Pisces.	Fishes.
	(b) Amphibia.	Frogs.
	(c) Reptilia.	Reptiles.
	(d) Aves.	Birds.
	(e) Mammalia.	Mammoth, seal, whales.

Protozoa.[1]—This is the lowest division of the animal kingdom. The organisms of this group consist of a single cell of jelly-like matter; and some protect themselves with a strong covering secreted from the sea-water.

Only those possessing a hard cover are preserved as fossils. Among these we have the *Foraminifera*,[2] which secrete a carbonate of lime covering, and the *Radiolaria*,[3] which form a hard case of silica.

The shells of the Foraminifera are shaped like flasks or flattened globes with a biconvex section, or like globes and flasks entwined.

The walls of the shells are pierced with numerous holes through which the

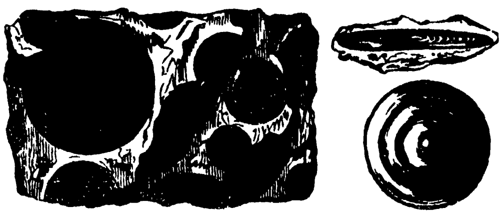


FIG. 152.—Nummulites, Lower Tertiary Species.

animal extends thread-like organs. The *Foraminifera* form important deposits on the floor of the deep seas; and they have played an important part as limestone builders in the earlier periods of the Earth's history, and as chalk builders in the Cretaceous.

Among the best-known genera of *Foraminifera* are *Dentalina*, *Nodosaria*, *Cristellaria*, *Globigerina*, *Rotalia*, and *Nummulites* (figs 151, 152).

The *Radiolaria* secrete siliceous skeletons that are often a geometrical framework of extreme beauty. They form deposits of ooze on the floor of the deep sea; and as fossils are found in cherts and other siliceous rocks.

Porifera.—This sub-kingdom includes the sponges, which are somewhat more complex organisms than the protozoans. The body is usually supported on a framework or skeleton of horny or siliceous fibres, the latter consisting of spicules that are composed of silica. In another group of sponges the skeleton consists of carbonate of lime.

The majority of the sponges are marine. The portions found fossil are usually the siliceous or calcareous spicules and fibres.

Cœlenterata.—This goup contains the Hydrozoans and Actinozoans, which are of immense geological importance. The *Hydrozoans*[4] include the *graptolites*,[5] which have long been extinct, but are of great value as a means of

[1] Gr. *protos*=first, and *zoon*=an animal.
[2] Lat. *foramina*=holes, and *fero*=I bear.
[3] Lat. *radius*=a ray.
[4] Gr. *hydor*=water, and *zoon*=an animal.
[5] Gr. *graphein*=to write.

determining the age of the rocks in which they occur. Graptolites (figs. 153–

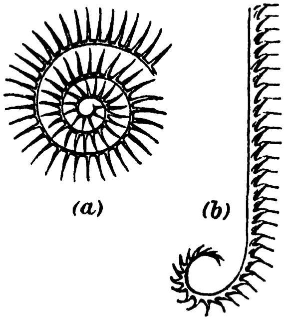


FIG 153.—(a) *Monograptus spiralis.* (b) *M. cyphus.*

FIG. 154.—*Diplograptus.*

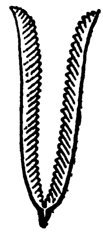


FIG. 155.—*Didymograptus.*

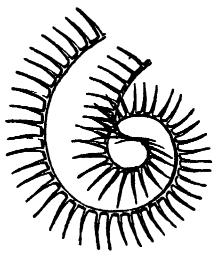


FIG. 156.—*Rastrites.*

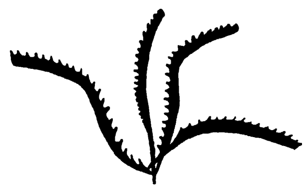


FIG. 157.—*Tetragraptus.*

157) are found in shales, slates, and argillaceous sandstones, in which they

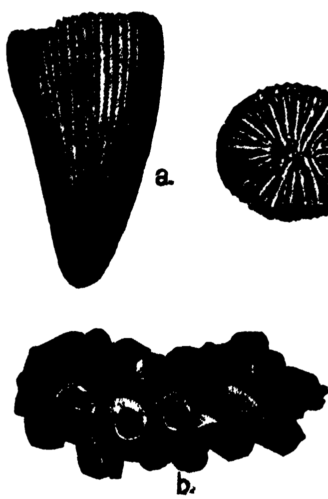


FIG. 158.—Showing corals.
(a) *Trochocyathus.* (b) *Oculina.*

occur as flattened bodies that are usually converted into a bituminous carbonaceous material.

The *Actinozoans* (fig. 158) include the well-known coral-builders; they consist of a soft body supported in a cup of carbonate of lime. They build up huge coral reefs and enormous masses of limestone. They are perhaps the most important of all living organisms considered as geological agents.

Echinodermata.[1]—These are, as the name implies, at least in part, spiny-skinned animals. They possess a calcareous covering made up of a number of

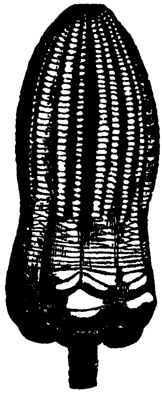


FIG. 159.—Fossil sea-lily. *Encrinus.*

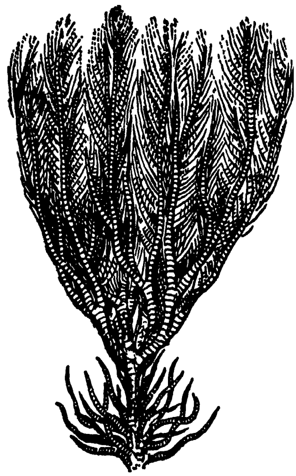


FIG. 160.—Fossil sea-lily. *Pentacrinus.*

plates. The portions found fossil are the spines and plates. The *Crinoidea*, *Echinoidea*, and *Asteroidea* are the chief classes of this sub-kingdom.

The *Crinoidea* [2] (figs. 159, 160), called crinoids or sea-lilies, usually consist of long flexible stalks with a calyx at the upper end. The calyx contains the internal organs of the animal, and is protected with plates symmetrically arranged. Round the calyx there is a number of flexible arms which, like the

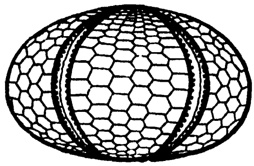


FIG. 161.—Fossil sea-urchin, *Palæchinus.*

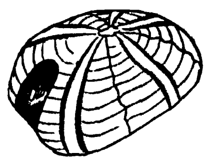


FIG. 162.—Fossil sea-urchin, *Nucleolites.*

stalk, are encased in calcareous plates. The animal is attached to objects on the sea-floor by the stalk, which is jointed and flexible. Broken arms and stalks of crinoids are sometimes so plentiful as to compose masses of limestone.

The *Echinoidea* [3] (figs. 161, 162) include the well-known Sea-urchins so often cast up on sandy beaches or seen in rocky pools below high-water mark. They are usually globular (fig. 161) or heart-shaped (fig. 162) animals enclosed in a spiny case or shell composed of closely-fitting calcareous plates. The spines, plates, and frequently whole shells, are found fossil.

[1] Gr. *echinos*=a hedgehog, and *derma*=skin.
[2] Gr. *krinon*=a lily, and Gr. *eidos*=like.
[3] Gr. *echinos*=a hedgehog, and Gr. *eidos*=like.

The *Asteroidea*[1] or Starfishes (fig. 163) consist of a central flattened disc with several radiating arms.

The *Ophiuroidea*[2] (fig. 164) are related to the Starfishes. They comprise a remarkable group of *Brittle-stars* in which the viscera are extruded from the arms. They consist of a central flattened disc-like body from which project five long flexible arms used by the animal as a means of locomotion.

FIG. 163.—Fossil starfishes, *Palæaster* (*Stenaster*) *obtusus* (Forb.), from the Cambrian, to the left, and *Palæaster* (*Urasterella?*) *asperrimus* (Salt.) to the right.

Annulata.[3]—The *annelids* or segmented worms are almost the only ones found fossil. Some of the annelids secrete calcareous tubes which have been preserved in shales and slates. The former existence of worms is also known by the fossil trails left in muds now hardened into shales, and by the worm-burrows made in sands now converted into sandstones.

Worm-burrows and trails are among the oldest known fossils. Many of the so-called fucoids which are found in rocks of all ages are probably the trails or the remains of tube-building annelids.[4]

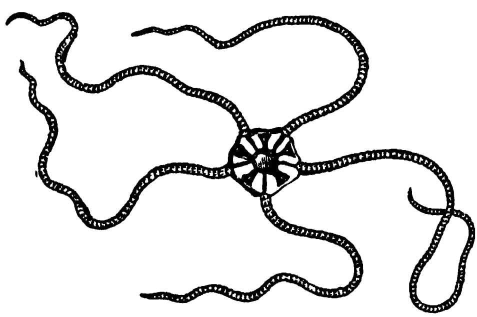


FIG. 164.—Showing fossil brittle-star, *Ophioderma.*

Molluscoidea.[5]—These comprise the *Polyzoa*[6] and *Brachiopoda*,[7] which are soft-bodied animals provided with a calcareous shell or covering. The two groups are extremely different and are classed in one sub-kingdom only on account of certain similarities in the development of their earlier stages of growth.

The *Polyzoa* (figs. 165, 166) or Sea-mats, sometimes called *Bryozoans*, are tiny animals living in a separate cell; but a number of individuals are united in a colony which may form an encrusting mat on the rocks on the seashore,

[1] Gr. *aster*=a star, and Gr. *eidos*=like.
[2] Gr. *ophis*=a snake, *ura*=tail, and Gr. *eidos*=like.
[3] Lat. *annulus*=a little ring.
[4] F. A. Bather, *The Geological Magazine*, Dec. 1911, p. 549.
[5] Lat. *mollis*=soft, and Gr. *eidos*=like.
[6] Gr. *polys*=many, and *zoon*=an animal.
[7] Gr. *brachion*=an arm, and *pous*, *podos*=a foot.

or on some other organism. They are found as fossils in rocks of all geological ages and in some periods formed reefs that are now limestones.

The *Brachiopoda* (figs. 167, 168) comprise one of the most important classes of fossil shells. They are also represented by living species, but occur in greater abundance in the Palæozoic and Mesozoic formations.

Brachiopods are soft animals enclosed in symmetrical bivalve shells, the valves of which are typically unequal in size. The larger valve is called the *ventral valve*, and the smaller, the *dorsal*. In most genera, the valves are locked together at the hinge. The ventral valve is usually perforated with a hole called the *foramen*, for the passage of a ligament by which the animal attaches itself to solid objects.

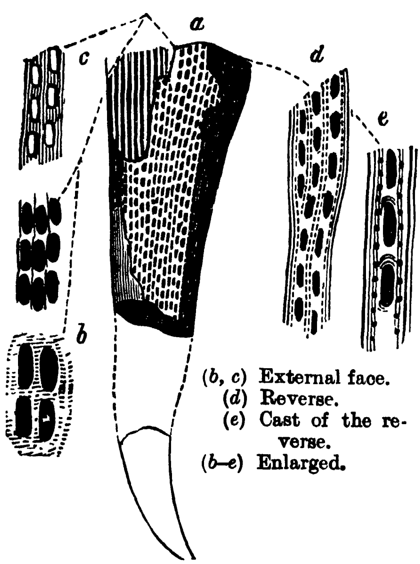


FIG. 165.—Showing fossil polyzoan, *Fenestella.*

FIG. 166.—Showing fossil polyzoan, *Monticulipora.*

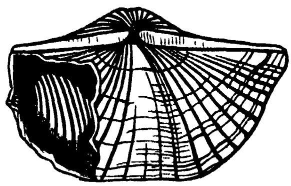


FIG. 167.—Fossil brachiopod, *Spirifer*, showing internal spiral loop.

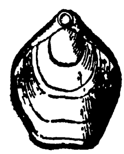


FIG. 168.—Fossil brachiopod, *Terebratula* (lamp-shell), showing foramen.

Most brachiopod shells contain an internal calcareous loop or spiral for the support of the breathing organs.

Mollusca.—This sub-kingdom is of immense importance on account of the plentiful occurrence of fossil types. It is represented by thousands of living and extinct species. All the land shells, and practically all the marine shells, so numerous in the shallow seas, are molluscs.

Nearly all molluscs possess a hard calcareous shell, and all have an elaborate nervous system and a heart. The three great divisions of the mollusca are—

(1) Lamellibranchiata.
(2) Gastropoda.
(3) Cephalopoda.

The *Lamellibranchiata* [1] (figs. 169–171) are found in freshwater lakes and the sea. They possess a bivalve shell which consists of a right and left valve. Among familiar shells of this class we have the *mussel*, *cockle*, and *oyster*.

[1] Lat. *lamella*=a little plate, and *branchiæ*=gills.

The *Gastropoda* [1] (figs. 172–174) are molluscs with only one shell or valve, and hence are spoken of as *univalve*. The shell may be basin-shaped, as in


FIG. 169 — *Protocardium.*

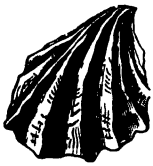


FIG. 170 — *Inoceramus.*

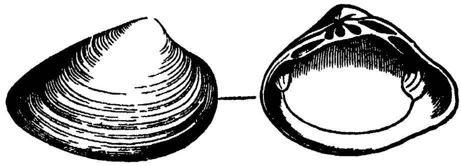


FIG. 171.—*Cyrena*, outer and inner view.


FIG. 172.—*Planorbis.*

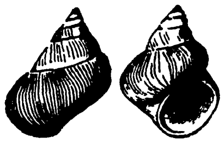


FIG. 173.—*Paludina.*


FIG. 174 —*Voluta.*

Patella; or coiled in a flat (fig. 172) or a turreted (figs. 173, 174) spiral. Some gastropods live on the land, some in fresh water, and a great many in the sea. All possess a distinct head with eyes.


FIG. 175.—*Nautilus.*

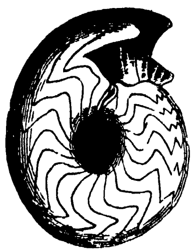


FIG. 176.—*Goniatites.*

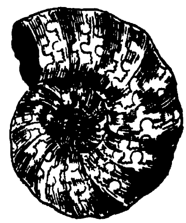


FIG. 177.—*Ceratites.*

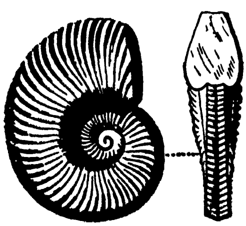


FIG. 178.—*Ammonites.*


FIG. 179.—*Scaphites.*

The *Cephalopoda* [2] (figs. 175–182) are the most highly organised of the mollusca. They include the *Nautilus*,[3] the *Octopus* or *Cuttle-fish*, the *Squid*,

[1] Gr. *gaster*=a belly, and *pous, podos*=a foot.
[2] Gr. *kephale*=a head, and *pous, podos*=a foot.
[3] Gr. *nautilus*=a sailor.

and two important orders that are now extinct, the *Ammonites*[1] and *Belemnites*.[2] The *Nautilus* (fig. 175) possesses a beautiful chambered shell.

The *Ammonites* (figs. 176–179) have shells resembling those of the Nautilus,

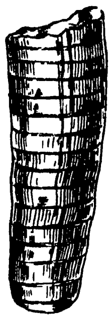


FIG. 180.—*Orthoceras.*

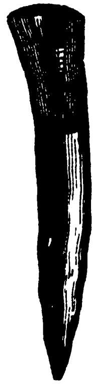


FIG. 181.—Guard of *Belemnites*, showing chambered phragmocone in top of cavity.

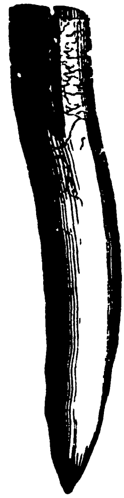


FIG. 182.—*Belemnitella.*

but more highly ornamented. The *Belemnites* appear to have resembled the modern squids. Both the Ammonites and Belemnites became extinct, the former about the close of the Mesozoic period, the latter in the earlier Tertiary.

Arthropoda.[3]—These are animals with jointed limbs and bodies divided into

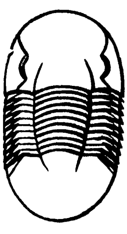


FIG. 183.—*Illænus.*

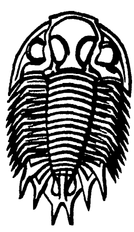


FIG. 184.—*Lichas.*

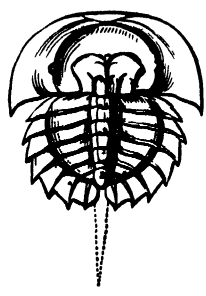


FIG. 185.—*Prestwichia.*

segments. They are divided into (1) the *Crustacea*, (2) *Arachnoidea*, (3) *Insecta*, and (4) *Myriapoda*.

The *Crustacea* include the crabs, lobsters, cray-fish, shrimps, and an important extinct group called *Trilobites* that are typically characteristic of the older Palæozoic formations. The Trilobites[4] (figs. 183, 184) owe their name to the

[1] So named after Jupiter Ammon.
[2] Gr. *belemnon*=a dart.
[3] Gr. *arthron*=a joint, and *pous*, *podos*=a foot.
[4] Gr. *treis*=three, and *lobos*=a lobe.

three-lobed arrangement of the body segments, the central lobe of segments being flanked by two other lobes, one on each side.

The Trilobites are the most distinctive of the older Palæozoic fossils, and are of great value as a means of determining the age of the rocks in which they occur.

The *Merostomata* [1] (figs. 185, 186), which are represented at the present day by the King-crabs, also occur in the older formations, a well-known form being the *Pterygotus* (fig. 186).

The *Decapods* [2] include the crabs and lobsters.

The *Entomostraca* [3] are minute crustaceans, many of which have the entire body enclosed in a shell composed of two valves united along the back by a hinge which permits the shell to be opened and shut at will. The best-known

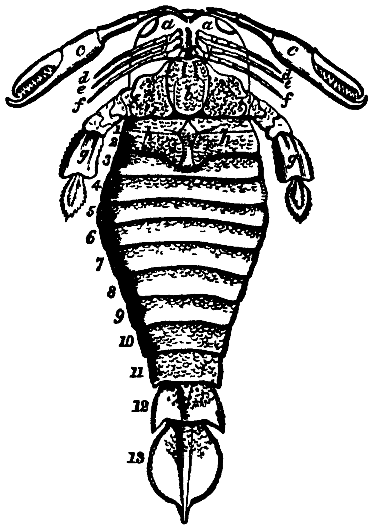


FIG. 186.—*Pterygotus*. (Restored by H. Woodward.)
For the meaning of the letters and numbers see explanation of Plate XXXI.

of this class are the *Water-fleas*, which are common in the oldest rocks, and are still represented by many living species.

Vertebrata.—These are subdivided into five great classes—

(1) *Pisces*=Fishes.
(2) *Amphibia*=Frogs.
(3) *Reptilia*=Reptiles.
(4) *Aves*=Birds.
(5) *Mammalia*=Mammals.

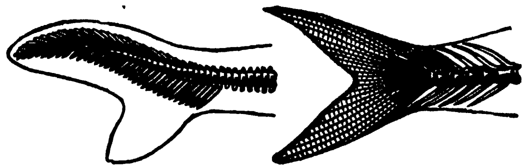
The *Pisces* or fishes are the oldest known vertebrates. The orders of fishes recognised in a fossil state are the *Placodermi*, *Elasmobranchii*, *Holocephali*, *Dipnoi*, *Crossopterygii*, *Ganoidei*,[4] and *Teleostei*.[5]

Among typical ganoids is the *sturgeon*, among Elasmobranchi the *shark*,

[1] Gr. *meros*=a thigh, and *stoma*=a mouth.
[2] Gr. *deka*=ten, and *pous*, *podos*=a foot.
[3] Gr. *entomon*=an insect, and *ostrakon*=a shell.
[4] Gr. *ganos*=brightness, and *eidos*=like.
[5] Gr. *teleos*=complete, and *osteon*=a bone.

both characterised by the possession of a *heterocercal* [1] (fig. 187, left) tail, *i.e.* a tail of asymmetrical shape, the spine entering only the upper and longer portion.

The ganoids first appear in the Silurian, and from the Devonian to the close of the Mesozoic they predominate among fossil fish.



Heterocercal. Homocercal.

FIG. 187.—Fish-tails.

The *Teleostei* are in many respects a more highly organised order than the ganoids, of which they are the lineal descendants, especially in having no more a cartilaginous but a bony skeleton. They first appear in the Lias and include most existing fishes. They are characterised by the presence of *homocercal* [2] (fig. 187, right) tails, *i.e.* a tail of symmetrical shape. They are typically represented by the trout, perch, herring, cod, mullet, and sole.

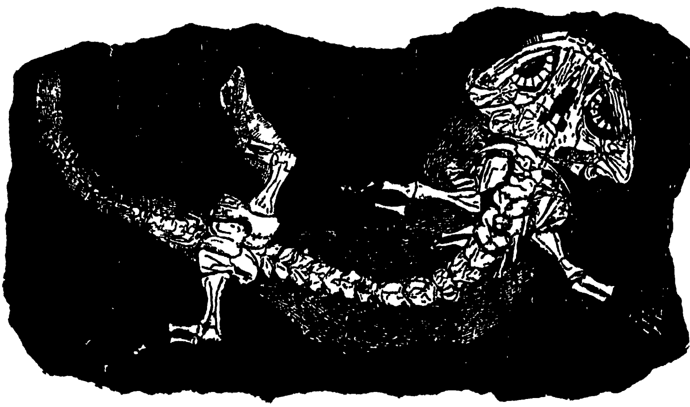


FIG. 188.—Showing the fossil salamander-like amphibian *Branchiosaurus salamandroides* (Fritsch), twice natural size.

The *Amphibia*,[3] sometimes called Batrachians, are animals that begin life as water-breathers, like fishes, and later become air-breathers. In this regard they form a connecting-link between the fishes and reptiles.

The amphibians are represented by the ancient and extinct order of *Labyrinthodonts* [4] (fig 188), and by the frogs, toads, and newts.

The *Reptilia* first appeared in the Carboniferous, but it was not till the Permian that they became numerous. They reached their fullest development in the Jurassic and Cretaceous epochs. The Mesozoic has often been called the *Age of Reptiles*.

[1] Gr. *heteros*=other, and *kerkos*=a tail.
[2] Gr. *homos*=the same or whole, and *kerkos*=a tail.
[3] Gr. *amphi*=both, and *bios*=life.
[4] Gr. *labyrinthos*=intricate, and *odous, odontos*=a tooth.

Many of the fossil reptiles assumed grotesque forms, and some of them grew to a gigantic size. Among the best known are the *Palæosaurians* [1] or ancient lizards, of which the *Tuatara* (*Sphenodon punctatum*) of New Zealand is the sole living representative; *Plesiosaurians*,[2] *Ichthyosaurians*,[3] and *Deinosaurians*.[4]

The *Aves* or birds first appeared in the Mesozoic. Many have lizard-like structure, and some of them have powerful beaks armed with teeth (fig. 189). Struthious birds of the ostrich, emu, and moa order have been found in the Lower Tertiary of Europe, and one from the London clay, called *Dasornis*, is

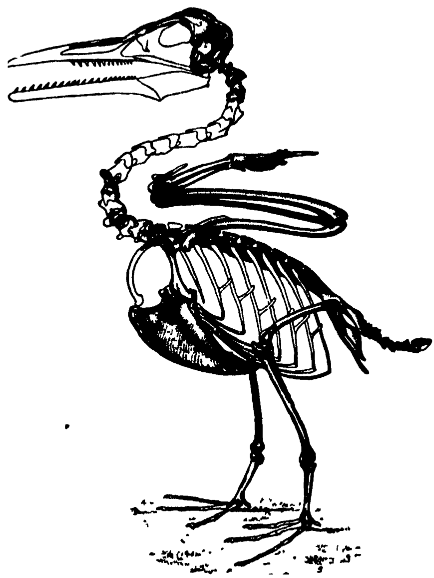


FIG. 189. Restoration of *Ichthyornis victor* (Marsh). From the Cretaceous of Kansas (*U.S. Geo. Surv.*).

considered by some to resemble the lately extinct *Dinornis* (moa) of New Zealand.

The oldest fossil bird is the *Archæopteryx* (fig. 190), from the Jurassic lithographic slaty limestone of Solenhofen, in Bavaria.

Mammalia.—This sub-kingdom includes the highest class of the vertebrata, and is characterised by the young being nourished for a longer or shorter time by milk or special secretion from the mammary glands.

The earliest evidence of mammals is met with in the Upper Trias, and in the Lower Jurassic the remains of small mammals become a little commoner. All the earlier forms are related to the existing Marsupials. In the Pliocene period the mammalian fauna assumes a modern appearance, comprising large tiger-like cats, bears, wolves, oxen, numerous antelopes, giraffes, deer, horse-like animals, and elephants. Most of the mammals of the Pleistocene belong to living genera.

The last group to appear includes the apes and man.

[1] Gr. *palaios*=ancient, and *sauros*=a lizard.
[2] Gr. *plesios*=near, and *sauros*=a lizard.
[3] Gr. *ichthys*=a fish, and *sauros*=a lizard.
[4] Gr. *deinos*=terrible, and *sauros*=a lizard.

VEGETABLE KINGDOM.

Plants are divided into two great groups—

I. Cryptogamia [1] or *flowerless* plants
II. Phanerogamia [2] or *flowering* plants

The **Cryptogams** are typically represented by the *ferns*, *horse-tails*, *mosses*,

FIG 190—*Archæopteryx Siemensi* (After Dames)

fungi, *diatoms*, and *algæ* or *sea-weeds* These are the oldest and lowest forms of plant-life. The calcareous algæ or nullipores are important reef builders.

The **Phanerogams** include all flowering plants that bear seeds, by means of which they reproduce themselves They are subdivided into two groups as under—

(1) *Gymnosperms*,[3] *i e* plants with naked seeds=*cycads* [4] or palms, and *coniferæ* or pines

[1] Gr *kryptos*—hidden, and *gamos*=marriage
[2] Gr *phaneros*=evident, and *gamos*=marriage.
[3] Gr *gymnos*=naked, and *sperma*=a seed.
[4] Gr. *kouki*=cocoa-palm.

(2) *Angiosperms*,[1] *i.e.* plants with seeds enclosed in a seed-case or vessel= oak, walnut, and most forest trees (except pines); roses and most garden plants.

Of these two groups, the *Gymnosperms* represent the lowest types of flowering plants.

The *Angiosperms* are divided into two well-marked and easily distinguished groups as follows:—

Angiosperms { (*a*) *Monocotyledons*,[2] with one seed-lobe=grasses, cereals, etc.
(*b*) *Dicotyledons*,[3] with two seed-lobes=oaks, beans, peas, etc.

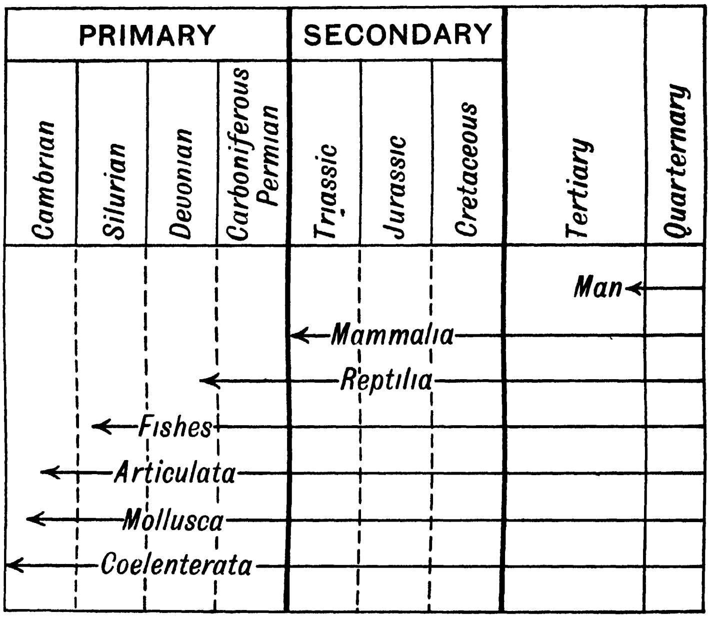


FIG. 193.

The *Monocotyledons* usually possess hollow stems, and increase in size by *internal* growth and elongation at the summit, and hence are often called *Endogens*.[4]

The *Dicotyledons* possess a solid stem, and usually increase in size by the yearly addition of a new layer of wood on the *outside*, and hence are called *Exogens*[5]

The leaves of the *Endogens* are usually distinguished by straight or parallel venation (fig. 191), and the leaves of the *Exogens* by reticulate or net-like venation (fig. 192).

The Palæozoic floras are mainly Cryptogamic, comprising ferns, mosses (?), and algæ. The Middle Mesozoic floras, besides Cryptogams, include numerous

[1] Gr. *angeios*=vessel, and *sperma*=a seed.
[2] Gr. *monos*=single, and *kotŭledon*=seed-lobe.
[3] Gr. *dis*=double, and *kotyledon*=seed-lobe.
[4] Gr. *endon*=within, and *genes*=born or produced.
[5] Gr. *exo*=outside, and *genes*=born.

FIG 191 —*Schizoneura australis* (Etheridge), showing straight venation of Monocotyledons or Endogens

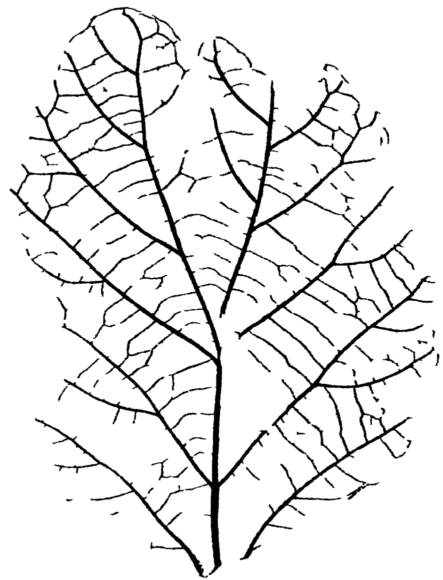


FIG 192 Leaf showing net like venation of Dicotyledons or Exogens

coniferæ (pines) and cycads (palms). The Cretaceous and Tertiary floras are characterised by a predominance of Phanerogams.

The diagram (fig. 193) approximately illustrates the progress of animal life throughout the geological record.

Uses of Fossils.

Perhaps the first and most obvious lesson to be gleaned from the study of fossils is the elementary truth that life, even in the earliest times, in its various functions and characteristics, differed in no way from the life of to-day.

Further, we observe (*a*) that the lowly types of life that appear in the oldest rocks have persisted through all geological times up to the present day; (*b*) that new genera of progressively higher types suddenly appear as we ascend the geological scale; and (*c*) that many genera have a limited range in time.

From our knowledge of the distribution and habits of related existing faunas and floras, we have no difficulty in distinguishing terrestrial and marine organisms, or the inhabitants of warm and arctic seas, or the littoral from the pelagic.

Hence the fossils contained in a rock-formation form a permanent record of the climatic and physical conditions prevailing at the time the sediments which enclosed them were being deposited. They tell of the former existence of continents, rivers, lakes, estuaries, and seas; of tropical heat and arctic cold.

Fossils as Time-Registers.—As stratified rocks are composed of more or less parallel layers of sediment that were laid down one after another, it follows that the lower beds must be older than those that overlie them. This simple truth embodies what is called the *Law of Superposition*, and by means of it the geologist is able to determine the chronological order or succession of stratified rocks. The only exception to this law is when strata have been inverted by acute folding.

In the year 1790, William Smith, as the result of an examination of the Jurassic rocks of West England, established the fact that there was a regular order in the succession of the beds, and that each bed might be identified by its fossils. This apparently simple discovery gave a new direction to geological investigation. It laid the foundation of modern Stratigraphical Geology, and established a principle which at once raised geology to the status of a science.

Subsequent investigation has shown that not only are the larger groups of beds distinguished by particular genera and species, but that particular horizons or layers may possess forms that are limited to them, and are therefore distinctively their own.

The Lias is now known to be divisible into zones, each characterised by one or more species of Ammonite. In the same way the Ordovician may be divided into horizons or zones, each distinguished by one or more species of Graptolite limited to it. Likewise the zonal distribution of fossils may be seen in the Chalk, and the same principle prevails throughout all the geological succession.

When once the order of succession of the strata in any region has been made out, the fossils found in the different beds become a valuable means of identifying the same, or contemporaneous, beds in other regions.

Lithological character alone is never a safe guide for the identification or correlation of distant groups of stratified rock. A group of beds may, like the Desert Sandstone of Queensland, present the same lithological characters over tens of thousands of square miles, and contain the same fossils throughout. Frequently, however, as already remarked in another chapter, a sandstone may

pass in the same plane into a shale, and a shale into a sandstone. The sandstone and shale are *contemporaneous*, but lithologically they are very different rocks. Moreover, the fossils in these rocks will possess the same general *facies*, minor faunal differences that may exist being due to the different conditions of deposition.

When, therefore, the chronological succession of the stratified rocks of the globe has been established, and the distinctive fossils of each group identified, the fossils become *time-registers*, by which the age of distant rock-formations may be determined without regard to their lithological character. In other words, when the fossils of a rock-formation in a new region have been examined, the geologist will be able by their means to fix the age of the rocks relatively to the general succession.

Homotaxis.

Investigation has shown that the general succession of animal and plant life, throughout geological time, has been the same over the whole of the globe. For this similarity of succession Huxley adopted the biological term *homotaxis*.[1] For example, the genera of corals, graptolites, trilobites, fishes, reptiles, brachiopods, and plants that characterise the rocks of Europe, appear in the same general order in America and Australia; but it does not necessarily follow that the groups of beds containing the same fauna in these distant lands are chronologically contemporaneous. The Devonian of Europe may overlap the Silurian of America, and may itself be overlapped by the Carboniferous of Africa. Homotaxis, therefore, means the correspondence of succession without identity of age.

If the same organic types appeared simultaneously over the whole globe, it is obvious that all rocks containing the same fossils would be coeval. But this postulate is inconceivable. It is more probable that particular genera made their first appearance in the Northern, or in the Southern Hemisphere, and slowly spread by various processes of dispersion from one hemisphere to the other.

As would naturally be expected, the marine faunas would show a closer parallelism than the floras, a circumstance due to the greater facilities for rapid migration possessed by marine inhabitants in a continuous sea, compared with the slower dispersion of terrestrial organisms, perchance checked by physical obstructions, such as wide stretches of sea and mountain-chains.

During the process of dispersion, the genera would to some extent be modified by accidents of climate and changes in the distribution of land and water, arising from earth-movements; and the slower the rate of migration, the greater would be the differentiation.

But contemporaneity is in some respects a relative term. Recent events, that are separated by a year, seem far apart, while events that took place before the Christian era seem close together, even when separated by many decades. The geological day is not measured by years, and events possibly separated by thousands of decades of our limited chronology seem to converge when viewed in the distant perspective of geological time.

The marine faunas, on account of their greater opportunity for dispersion, have usually been taken as the basis of comparison and correlation throughout the geological record. If we regard the *genus* as the organic unit and not the *species*, which is merely the variant arising from adaptation to local environment, we cannot fail to be impressed with the extraordinary similarity of the marine types existing to-day in the corresponding latitudes of the two hemi-

[1] Gr. *homos*=the same, and *taxis*=arrangement.

spheres. And when we find that the same correspondence of marine types, as between such widely separated regions as Western Europe and Australia, can be traced down through the Pliocene, Miocene, Eocene, Cretaceous, Jurassic, and Triassic formations without a break, or the interpolation of a fauna in one region that is not represented in the other, we are forced to conclude that in this portion of the geological record there is little room for chronological divergence. The parallelism of the more primitive Palæozoic faunas was doubtless as close, if not closer, than that of later ages.

The divergence of the successive land faunas of the two hemispheres might possibly be considerable in special areas in view of the greater opportunity for the survival of ancient types in regions isolated by deep seas, great mountain-chains, or other geographical barriers.

The great Australian continent, on account of its permanency and isolation, is pre-eminently a land of survivals. Here we have a remarkable persistence of the marsupials—a primitive type of mammal—and an equally ancient type of flora.

Summary.

(1) The remains of plants and animals that have been preserved in rocks are called *fossils*.

(2) Most fossils are sea-shells and other marine organisms. In many rocks, particularly in limestones and those composed of fine sediments, the original shell or calcareous covering of the animal is preserved ; but in rocks of a porous character the shells have frequently been dissolved, leaving only an external or internal cast, or perhaps both.

(3) The rocks most frequently found fossiliferous are limestones, clays, marls, shales, and sandstones.

(4) The fossils are contemporaneous with the sediments or rocks in which they are enclosed. But a Cretaceous rock may contain blocks of stone that enclose Silurian fossils. Such fossils are called *derived fossils*.

(5) Igneous rocks do not contain fossils, but fossiliferous blocks of stratified rock are not uncommon among the fragmentary detritus ejected by volcanoes. Such blocks were doubtless torn from the sides of the volcanic vent.

(6) The most important fossils in the animal kingdom, beginning with the simplest forms, are foraminifera, graptolites, corals, sea-lilies, brachiopods, molluscs, fishes, reptiles, birds, and mammals ; and in the vegetable kingdom, ferns, lycopods, horse-tails, cycads, pines, and forest trees related to existing types.

(7) The chronological succession of stratified rocks is determined by *superposition*. When the order of succession of stratified rocks has been determined, the contained fossils become of great value for the determination of the age of rock-formations in distant regions.

(8) The faunas and floras of geological time appear throughout the globe in the same orderly succession. Although genera may appear in the same order in the Northern and Southern Hemispheres, it does not necessarily follow that they are contemporaneous. Time would be required for dispersal from the cradle where the new genera appeared. But when a great succession of strata in widely separated regions contains faunas that appear in the same order in each region, we seem justified in assuming that though bed for bed the strata may not lie in precisely the same time-plane, for all practical purposes they are geologically contemporaneous.

The completeness of the geological record in the Northern and Southern Hemispheres does not leave much room for chronological divergence.

CHAPTER XX.

CONFORMITY AND UNCONFORMITY.

Conformity.—Beds of sediment that have been laid down in such a way that their stratification-planes are parallel with one another, are said to he *conformable* (fig. 194).

The meaning to be gathered from conformable stratification is that the deposition of the sediments composing the beds was continuous and uninterrupted, which is only another way of saying that no change of any moment took place in the physical geography of the area during the period covered by the deposition of the beds in question.

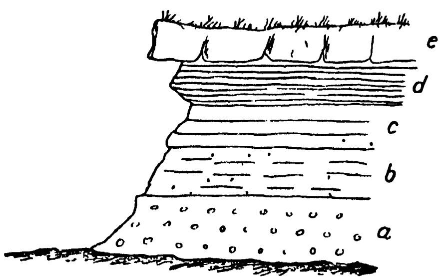


FIG. 194.—Showing conformable series of strata.

The beds may be laid down on a slowly sinking or rising sea-floor, and coarse sediments may be followed by fine, or fine by coarse, due to the overlap resulting from an advancing or receding shore-line, but the distinctive life of each zone will remain the same so long as the same physical conditions prevail.

Hence it is found that in a series of conformable strata there is no violent biological break or change in the character of the contained fauna, always provided that in a vast pile of sediments representing a great range of time, some of the older forms of life may disappear before the invasion of newer and more vigorous kinds of life in the uppermost strata.

Unconformity.—When a series of conformable strata rests on the upturned, folded, or denuded surface of an older series of beds, there is said to be an *unconformity* between the two formations. The younger series lies *unconformably* on the older.

In fig. 195 the younger series, *a*, *b*, *c*, rests unconformably on the upturned edges of the older series, *d*, *e*, *f*.

The meaning to be gathered from this relationship is that the older formation was deposited, consolidated, elevated, denuded, and again submerged before the younger formation was laid down. That is, the old sea-floor on which beds *d*, *e*, *f* were deposited was elevated so as to form dry land, remained dry land for some time, and then became submerged before the deposition of beds *a*, *b*, *c* began.

An unconformity is therefore an evidence of a *break* in the continuity of the geographical conditions which existed when the older formation was deposited. This break may represent a period of time of greater or less duration, depending on the rate of uplift, the length of time the raised

sea-floor remained dry land, and the rate of the subsidence. That is, some unconformities may be slight, others very great.

If the uplift is slow, the sediments as they emerge from the sea may be little disturbed in their stratification; and denudation may wear away only the upper layers before subsidence begins. In this case the unconformity will be slight, as the new sediments will be laid down with their bedding planes almost parallel with those of the older partially denuded formation.

But if the uplift is of long duration, permitting the land to be worn down by denudation to a surface of low relief before subsidence takes place, the newer sediments will be laid down on an approximately level surface of the older formations. In this case the older strata will be separated from the younger by a well-marked unconformity. When the older formation has been tilted or folded before the deposition of the younger, the unconformity may be as conspicuous as that shown in fig. 195 between points *d* and *a*; or in fig. 197 between *b* and *a*.

Unconformity is therefore a record of a change in the geographical conditions in the area of deposition.

A physical break, as might be expected, is usually marked by a diversity in the faunas of the unconformable rock-formations. It is obvious that the uplift of the sea-floor, after the deposition of the older sediments, must cause the migration or destruction of the existing fauna.

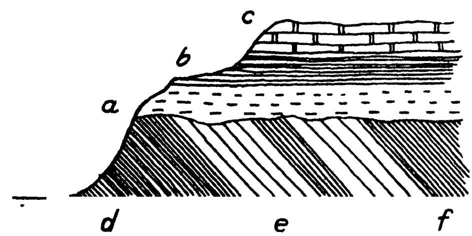


FIG. 195.—Showing an unconformity.

When submergence once more takes place and the deposition of sediments again commences, the new sea-floor will be peopled by colonists from the neighbouring seas. If the unconformity is slight, the incoming fauna will be the lineal descendants of the fauna displaced by the uplift; but if the unconformity is decided, the new fauna may possess little or no relationship to the old, and this constitutes what is called a *palæontological break* or unconformity.

Evidences of Unconformity.—The most obvious proof is usually the discordance of the stratification-planes of the two formations. Moreover, as the older rocks were exposed to denudation before the deposition of the younger began, fragments and pebbles of the older rocks are frequently found in the younger.

Beds of conglomerate or grit in many cases form the bottom or basal members of a rock-formation. Hence they frequently occur at the break between two unconformable formations.

Thick beds of coarse conglomerate interbedded with shales or sandstones, although they do not indicate a physical break in the continuity of deposition, clearly mark a considerable change in the local geographical conditions arising either from elevation or subsidence.

When a younger series wraps around the edges of an older series, there is clear evidence of unconformity, even though no actual contact may be exposed between the two formations. Unconformity is also shown by the younger series overlapping the various members of the older.

Fault-fractures, mineral lodes or igneous dykes that are present in the lower formation, but do not penetrate the overlying series, afford convincing proof of interrupted deposition of sediments, and therefore of unconformity.

The fossil fauna of the different rock-formations is now so well ascertained that the unconformable relationship of two series of strata can be postulated even when no physical break is apparent. For example, when we find rocks with a Triassic fauna resting on Silurian strata, or rocks with a Tertiary fauna in contact with a Cretaceous system, we know that the Trias is unconformable to the Silurian, and the Tertiary to the Cretaceous, even if we are unable to trace the physical break in the field.

Interformational Unconformity.—Physical unconformity is sometimes seen in certain places between members of the same formation. Such discordance may have arisen from local uplift, or from the wash-out caused by tidal waves, temporary diversion of sea-currents, hurricanes, or cloud-bursts.

Deceptive Physical Conformity.—The actual line of contact between two rock-formations is rarely well exposed, being only seen to advantage in sea-cliffs, rocky gorges, and quarries. More often the junction-line is obscured with soil, loam, glacial drift, residual clays, or the peaty accumulations of forest or other vegetation. Care must therefore be exercised in the determination of the physical relationships of two adjoining formations, and in no case should final pronouncement be made on the evidence of one exposure.

Every formation represented in the geological record is distinguished by its own peculiar assemblage of fossil-remains, by means of which it can always be recognised, however complicated and obscure its stratigraphical relationships may be. Hence in the determination of relationships the palæontological evidence is of supreme importance.

Mere parallelism of the stratification-planes of two formations does not necessarily imply conformity. It may easily happen in the case of two systems not separated by a great interval of time, that steady uplift of the older to a height not far above sea-level in a region of quiet denudation, followed by steady subsidence, may result in the deposition of the younger in layers that rest on the older with apparent parallelism. Such deceptive conformity is found in South-East England and at Waipara, New Zealand, in Lower Egypt, as between the Cretaceous and Eocene in Ireland as between the horizontal Trias and Upper Cretaceous near Belfast; and in South Africa, as between the Ecca Beds of Upper Carboniferous age and the Lower Cretaceous, as exposed at Worcester, in Cape Colony.

On the east side of the Libyan basin, the outcrops of the Upper Cretaceous and Lower Eocene limestones may be traced for scores of miles running parallel with one another and with the underlying quartzose Nubian Sandstone. At many places the inclination of the Cretaceous and Eocene is so nearly the same that no physical break can be detected between the two systems; while at other places the unconformity is quite distinct. Nevertheless the palæontological break is everywhere great.

It is obvious that when subsidence took place the old Cretaceous basin became an Eocene basin. When the tilting of strata takes place after the deposition of the younger beds, there may be little or no apparent stratigraphical break, except in places where the Cretaceous strata have been subject to considerable denudation.

In fig. 196 Tertiary beds are seen resting on the Cretaceous. As viewed near C and along section A—B, the two systems appear to be conformable, and the true relationship is only disclosed when the whole section from C to D is examined.

Thus we see that the physical break between two systems may not be everywhere equally marked, and in some places its detection may be impossible.

Moreover, there may be apparent conformity in places arising from

accidents of folding or form of denudation. For example, in fig. 197 beds *a* are highly unconformable to beds *b* between points *b* and *d*, but between *d* and *c* there is apparent conformity.

The type of unconformity shown at *c*, fig. 197, where the older rocks are not folded, is sometimes called a *disconformity* (Grabau); but perhaps the term *para-unconformity* (Crosby) is a better expression for the physical parallelism that exists between two palæontologically unconformable groups of strata.

Where the older strata have been folded and denuded before the younger strata were deposited (*b*, fig. 197), we have a readily recognisable physical unconformity; and for this type of unconformity the term clino-unconformity has been proposed.

Many notable examples of deceptive conformity are found in regions where *orogenic* or mountain-building movements have thrust the rock-formations into great folds. All the stratified rocks involved in such folds are tilted so as to run parallel with the main axes of elevation, and in this way a parallelism of stratification is obtained even among rocks of the most diverse ages. In this way Triassic or even younger formations may appear conformable to older Palæozoic rocks.

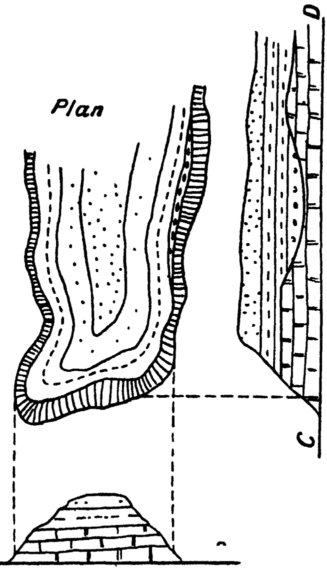


FIG. 196.—Plan and sections showing deceptive conformity.

In the Bernese Oberland, on the west side of the Jungfrau, the strips of Eocene nummulitic limestone are infolded so as to appear to be conformable to the Malm or White Jura in which they are infolded. Similarly the Lower Tertiaries infolded among the mica-schists at Moonlight Creek[1] in Otago possess for many miles the same strike

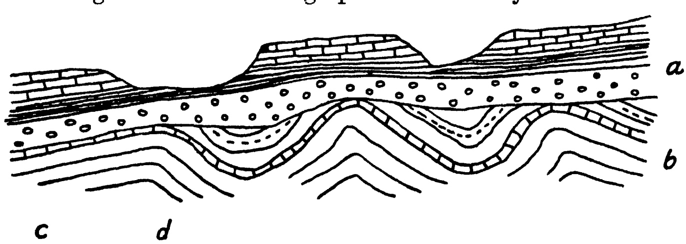


FIG. 197.—Showing deceptive conformity of two unconformable rock-formations.

and dip as the older rocks, everywhere exhibiting a striking example of deceptive conformity, as shown in fig. 198.

Value of Unconformities.—We have already found that a great succession of strata with its contained fossils is a record or history of the sea in which the deposition took place. It proves that deposition was *continuous*, hence the chronological importance of such a succession.

But an unconformity is no less valuable. It tells us of a *break* in the

[1] J. Park, "Geology of Queenstown District," *Bull.* 7, *N.Z. Geol. Surv.*, Wellington, 1909, pp. 61–65.

continuity of deposition arising from the uplift of the sea-floor whereby the previously existing area of denudation was augmented. It fixes the dates of earth-movements, and enables us to outline approximately the form of the land-areas and sea-margins in past geological times.

The obvious effect of the uplift of the sea-floor with its newly formed sediments will be to increase the previously existing area of dry land, thereby increasing the area of denudation. Denudation will be more active than ever, and its products will be deposited on the new sea-margin which, before the uplift, may have been the floor of a deep or shallow sea.

From this we gather that unconformities are not necessarily world-wide, for though uplift may cause deposition to cease in a particular area, its ultimate effect is merely to shift the scene of deposition to some other portion of the sea-floor. Therefore by tabulating the various series of strata and the unconformities in some island or continent, we are able to tell when that area was submerged and when it was dry land. The breaks, or lost chapters, as unconformities have been aptly called, can only be filled in by the study of some area where deposition was continuous.

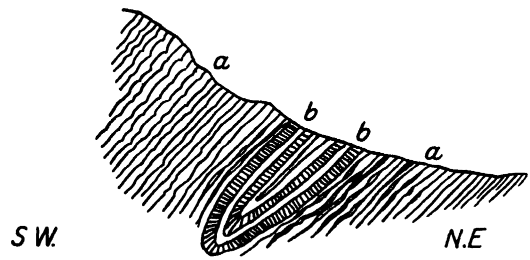


FIG. 198.—Showing deceptive conformity due to involvement of Tertiaries among older Palæozoic mica-schists, Moonlight Creek, New Zealand.

(*a*) Mica-schist. (*b*) Tertiaries.

In some continents the geological record is almost complete; in others it is broken and imperfect. A full record tells us that the area was marginal to some land of great permanence that may have been subject to oscillations, but was never completely submerged, being an area of denudation, though perhaps of constantly varying form, from the earliest geological times.

A region containing an imperfect record is an area of still greater permanence, for its persistence as dry land is the main cause of the imperfection of the record, for obviously while it remained dry land it could not be an area of deposition.

But all parts of a continent are not equally stable, as shown by the circumstance that the record may be comparatively complete in one part and scanty in another.

Changes of Life during Geological Time.—It is sometimes found that the same or closely related faunal types persist through a considerable thickness of strata, which may be partly due to the rapid accumulation of the sediments, and partly to the continuance of the same physical conditions of deposition.

In other cases changes in the fauna occur in every few feet of rock, which would tend to show that the rate of deposition was relatively slow compared with the organic changes in the fauna. This rapid change of faunal types is met with in many fine-grained shales and in certain cherts, all of which would appear to have accumulated slowly in deep water far from land.

In a pile of conformable strata consisting of basal conglomerates followed by sandstones, clays, and limestone, the basal rocks will be distinguished by the prevalence of littoral shells. If a band of conglomerate follows the clays, there will in all probability be a reappearance of the prevalent types of the lower conglomerate; and if this conglomerate is followed by clays, these

will probably contain many of the dominant genera of the lower clays. In other words, with a recurrence of the same conditions of deposition, there is frequently a reappearance of the same faunal types by migration from the neighbouring seas. Just how much these types are modified will depend on the lapse of time represented by the intervening strata.

Some forms of life, like the Nautilus and Shark, have a great vertical range in geological time; while others, like many species of Ammonites and Belemnites, have a wide geographical distribution in some particular horizon or time-plane, but a limited vertical range.

The chronological classification of the stratified rock-formations is mainly based on the interpretation of the physical breaks and the progressive organic changes observed throughout the geological record. The rocks are the monuments, and the fossils the hieroglyphics, by means of which the geologist is enabled to divide the history of the Earth into eras, periods, and epochs, and to unravel the successive physical and organic changes that have taken place since the beginning of geological time.

Permanence of Continents.—It has now been established as geological axioms—

(*a*) That sedimentary rocks are composed of detrital material derived from the denudation of land areas.

(*b*) That sedimentary rocks are marginal to the land from which the material composing them was derived.

The obvious inference to be drawn from these simple truths is, that the continents, though constantly varying in size, shape, and height, through subsidence and uplift, have existed as land areas from a remote geological period.

It would almost appear as if the present continents and deep seas were developed by the first crumpling of the Earth's crust, arising from cooling and contraction, at some period long antecedent to the formation of the oldest known stratified rocks.

The continents have been subject to denudation throughout all time, and the younger stratified formations have been derived from the waste of the older. The same material has appeared re-sorted in different rock-formations in different geological ages. The continents have been wasted while being reconstructed, and have thereby been preserved from destruction by the continual accumulation of new material supplied from their own ruin. In this way they have maintained their individuality.

The preservation of the continents has been solely dependent on oscillations of the land. For it is obvious that if the continents had remained stationary, let us say, since the close of the Palæozoic, neither rising nor sinking, they would in the course of time have been reduced to a plain of marine denudation. They would eventually have disappeared beneath the surface of the sea, and ceased to exist as land-areas. Deposition would then have come to an end, and from then onward there would be a complete blank in the geological succession, and a cessation in the progressive development of all animal and vegetable life.

Uplift and denudation are doubtless responsible for the incompleteness of the geological record, but it is certain that without continual oscillation and deposition there could be no succession of stratified rocks and therefore no record of organic life.

SUMMARY.

(1) When sediments are laid down on the floor of the sea or a lake in layers that lie parallel with one another, they are said to be *conformable*. The bottom

layers will be older than the upper, but there will be no break in the continuity of the succession.

(2) When a series of sediments is uplifted so as to become dry land and is subjected to denudation in such a way that its surface becomes worn into hollows and ridges, eventually submerged and then covered with a succession of sediments, the new sediments are said to be *unconformable* to the older underlying series.

When the older series of beds is not only eroded but also tilted by Earth-movements before the younger series is laid down on it, the unconformity is considerable, and probably represents a long interval of time between the deposition of the two series.

(3) An unconformity marks a physical break in the continuity of the local conditions of deposition. Uplift causes a migration of the marine fauna to adjacent seas. If the uplift last a considerable time, there may be recognisable change in the character of the fauna when submergence once more permits deposition to begin in that area.

(4) All sedimentary rocks are marginal to continental areas, and all are composed of material derived from the waste of older rocks. From this it is inferred that continents, though constantly varying in size and shape due to oscillations, have existed from the remotest geological times.

PART II.

HISTORICAL GEOLOGY.

CHAPTER XXI.

HISTORY OF THE EARTH.

Division of Geological Record.

WHEN studying an ancient language, the student as a first step must acquire a knowledge of the form of the written characters, of the significance of each character standing by itself, and of the meaning to be attached to a number of the characters when placed together. And so it is in geology. The study of rocks and the geological processes involved in the formation of rocks; of fossils, and the preservation of fossils, is the preliminary but necessary preparation that must be undertaken before we can successfully read the past history of the Earth as presented in the geological record. In geology the rocks are the monuments, the fossils the records; and when we have acquired a working knowledge of the A B C of the science, we are able to interpret the writing which unfolds a fascinating story of sunshine and shower, of brooks and rivers, of lakes and seas, of jungle and forest, of deserts and swamps, of volcanoes and earthquakes. Moreover, we further discover the wonderful procession of life that has peopled and clothed the Earth throughout the geological ages.

The geological history of the Earth from the earliest times is a record of uplift and subsidence, of retreating and advancing seas, of denudation and deposition.

During subsidence the sea advanced on the land, and the conditions of deposition that prevailed were marine. During uplift the sea retreated, and large inland seas and basins were enclosed, and in these the conditions of deposition were lacustrine or terrestrial. Frequent alternations of uplift and subsidence, commonly spoken of as oscillations of the land, often led to the deposition of alternating marine and terrestrial beds.

Uplift increased the size of the continents and consequently augmented the area of land exposed to denudation. Conversely, subsidence diminished the area of the dry land exposed to denudation.

The Gaps in the Record.—The history of the Earth must be read from the story of the rocks and their *fossil contents* in the same way as ancient Egyptian history is interpreted from the different types of sculpture and pottery buried in the successive layers of debris that cover the sites of the ancient cities and temples. On some sites we find evidence of unbroken occupation through a

long succession of dynasties, in others there are wide gaps that mark periods of desertion and ruin. And so it is with the geological record. In some regions the succession is relatively complete, in others it is fragmentary and full of gaps. In most continents the geological record is incomplete, but fortunately the gaps in the different regions do not always coincide, or occur in the same place in the succession ; hence we are able by a bit of patching to build up a record that, while admittedly imperfect, nevertheless affords a valuable synopsis of the physical geography and life of the Earth from the remotest times.

Before we proceed further, let us clearly understand what is meant by gaps in the stratigraphical succession. In one part of a continent, the Palæozoic formations may be well represented and followed directly by the Tertiary formations resting on a highly denuded surface of the older rocks. Here we have a gap or unconformity representing the whole of the Mesozoic era ; and from this we gather that one of two things has happened. Either the sea-floor in this region was uplifted after the close of the Palæozoic and remained dry land throughout the whole Mesozoic era, thus preventing the deposition of sediments, or else deposition was continuous for a portion of the Mesozoic, but the sediments thus formed were swept away by denudation during an interval of uplift before the deposition of the Tertiaries began. So far as the geological record is concerned, the result is a complete blank from the close of the Palæozoic to the beginning of the Tertiary era.

In another portion of the same continent we may find the Palæozoic rocks followed in orderly succession by all the Mesozoic formations ; hence, when we make up the stratigraphic succession for the whole continent, we are able to show a complete record.

The gaps in the stratigraphical succession in any given region are due either to sweeping denudation prior to the deposition of the younger unconformable strata, or to uplift, which prevented the deposition of sediments.

Uplift does not always take place at a uniform rate over a whole continent. One border may rise more rapidly than another, thereby affording an example of what is called *differential uplift.* Or one side of a continent may rise and the other sink, the movement resembling the tilting of a plank laid across a beam. In this case sediments will be deposited on the sinking sea-floor ; while, on the uplifted side, not only will there be no deposition of sediments, but the strata newly raised from the sea will be worn away, thereby accentuating and widening the gap that will exist before subsidence once more permits deposition to take place in that area.

Deposition of sediments has been continuous around the shores of the continents ever since they came into existence ; but the sediments have not accumulated as a continuous pile in any one place on account of the frequent oscillations of the land.

Uplift does not cause a complete cessation of deposition everywhere, for it is obvious that while dry land and seas exist, the products of denudation must be carried to the sea. Therefore, although uplift may cause a cessation of deposition in one place, its general effect is merely to shift the scene of deposition to the adjacent seas. Hence it is that gaps in the succession in one place are represented by sediments laid down in some other area. But the sediments that should fill the gaps have not always been preserved, or if preserved, they are not accessible. In some regions they have been removed by denudation, in others they have become obscured in earth-folds or submerged beneath the sea. Hence it happens that with all the patching that research has made

possible, there still remain many gaps in the stratigraphical succession that cannot be filled.

Even if the stratigraphical succession were complete, it is certain that the record of life contained in the rocks would still be imperfect, for we know that only a small proportion of the organisms that lived in past times have been preserved as fossils. Our knowledge of the marine faunas is imperfect, and of the land faunas, meagre and fragmentary, the opportunity for preservation of terrestrial animals being small compared with that of organisms living in the sea.

Unconformities represent gaps in the succession of stratified rocks during which there is no record of the contemporaneous fauna and flora. An unconformity is merely a lapse of time of which there is no local record. It does not measure the interval, the duration of which can only be demonstrated by the fossil evidence.

When the characteristic fossils of the geological record have once been determined, the fossil evidence may prove the existence of gaps where they are not physically apparent. That is, deceptive conformity can frequently be proved by the fossil evidence.

The Geological Record.—Superposition is the only basis of stratigraphical succession.

The order in which the different layers of debris occur on the site of a buried city is of greater importance than the remains of pottery and works of art found in each layer, for obviously it is only after the proper order of succession of the different layers has been ascertained and verified that the contents become of chronological value. When the order of stratigraphical succession of a pile of strata has been definitely ascertained, and the characteristic fossils of the different beds determined, the fossils at once possess a chronological value and become useful for the fixing of the age of strata in distant regions.

It is now known that certain fossils occur only in certain groups of beds, and advantage has been taken of this truth to divide the geological record into *eras*, *periods*, and *epochs*, in the same way as historic time is divided into empires, dynasties, and reigns, or as a book is divided into chapters, paragraphs, and sentences. It is well to remember that the subdivision of geological time is only an empirical arrangement intended to facilitate the study and investigation of the past history of the Earth as revealed by the stratified rocks and their fossils.

Stratified rocks are arranged in *groups* which are subdivided into *systems* which in turn consist of *series*. In many cases a *series* is divided into *stages*, *i.e.* upper, middle, and lower divisions; and sometimes a stage is found to consist of recognisable *zones*, each characterised by distinctive fossils limited to it.

The equivalent divisions of time corresponding to groups, systems, series, etc., are as follows:—

Analogy.	Geological Time.	Strata.	Example.
Book, .	Era	=Group,	*e.g.* Mesozoic Group.
Chapter, .	Period	=System,	*e.g.* Cretaceous System.
Paragraph, .	Epoch	=Series,	*e.g.* Chalk.
Sentence, .	Age	=Stage,	*e.g.* Upper Chalk.
Line, . .	Stage	=Zone,	*e.g.* Zone of *Belemnitella mucronata.*

When we speak of the *Cretaceous Period* we refer to a particular interval

of geological time; but when we speak of the *Cretaceous System* we have in mind the assemblage of strata formed in the Cretaceous Period.

Geological time is divided into four grand *eras* or books, which are separated by unconformities or by great palæontological changes in the fauna and flora. Each book is subdivided into chapters or *periods*, and each chapter into paragraphs or *epochs*. In each paragraph there may be one, two, or more sentences or *ages*, and each sentence may consist of one or more lines, i.e. *time-planes* or *stages*.

Epoch.	Period.	Stage.
Cainozoic.	Quaternary.	Recent.
		Pleistocene.
	Tertiary.	Pliocene.
		Miocene.
		Oligocene.
		Eocene.
	Palæontological Break.	
Mesozoic or Secondary.	Cretaceous.	
	Jurassic.	
	Triassic.	
	Palæontological Break.	
Palæozoic or Primary.	Permian.	
	Carboniferous.	
	Devonian.	
	Silurian.	
	Ordovician.	
	Cambrian.	
	Unconformity.	
Eozoic or Archæan.	Algonkian or Torridonian.	
	Unconformity.	
	Laurentian or Lewisian.	

Such terms as Permian, Devonian, etc., are time-names and cover vast æons. When a rock is said to be of Miocene age, a reference to the table will show that it is comparatvely young; whereas a rock of Silurian age is one of great antiquity.

Some of the names of the periods are lithological, as Cretaceous and Carboniferous; some have a numerical origin like Trias; but the majority are derived from the names of the localities or regions where the rocks of that particular age are typically developed. The last, which are the best adapted for general use, comprise Cambrian, Silurian, Devonian, Permian, and Jurassic, which are names generally adopted by all geologists. But whatever their origin, it must always be borne in mind that these names have no lithological significance The Silurian period, for example, is merely an interval of time of unknown duration, and the rocks ascribed to it in one place may consist of conglomerates, sandstones, and shales; in another of limestones, shales, etc.

Further, the periods do not represent equal intervals of time any more than the reigns of the kings in history.

Geological time cannot be measured in years. All attempts to gauge the age of the Earth since it became habitable on the basis of the rate of deposition of sediments in deltas and estuaries have ended in failure. All that can

be safely postulated is that the Tertiary era may cover several million years, and the whole geological record perhaps scores of millions.

SUMMARY.

(1) The primary object of the study of rocks, fossils, and geological processes is to enable the student to unravel the past history of the Earth.

(2) The unconformities or gaps in the geological record are intervals not represented by sediments. The gaps may be due to uplift, or to denudation, or to both. When no sediments are laid down, there is no record of the fauna or flora of the interval covered by the unconformity; consequently stratigraphical unconformity is usually marked by a palæontological break.

Unconformities do not measure time. The intervals they represent can only be estimated in a relative way from the extent of the break in the succession of life.

(3) Superposition is the only true basis of stratigraphical succession. When the order in which the rock-formations occur has once been determined, the fossils contained in them assume a new value. And since the succession of organic types throughout the geological record has been definitely ascertained and is the same in all parts of the globe, fossils are of great value in fixing the age of strata wherever they occur, or however involved they may be in crustal folds.

(4) The different groups of strata are characterised by certain distinctive fossils, and advantage has been taken of this to subdivide geological time into eras, periods, and epochs.

(5) The periods are not of equal length any more than the reigns of the kings of history. Moreover, the time that has elapsed since the Earth became habitable cannot be estimated in years, but is vast and may possibly amount to many score million years.

CHAPTER XXII.

EOZOIC[1] ERA.

THIS group includes all the rocks of pre-Cambrian age that reach the surface or have been laid bare by denudation.

The Eozoic rocks are not only the oldest and thickest, but also the most widespread of all the rock-formations taking part in the structure of the Earth's crust. Even where not exposed at the surface, it may safely be assumed that they form the basement on which all the younger formations rest.

In Canada these ancient rocks occupy an area of nearly 2,000,000 square miles, and have an estimated thickness of over 50,000 feet. Elsewhere they occur in numerous isolated patches, some of considerable extent in the British Isles, Scandinavia, Bohemia, Alps, Himalayas, China, Andes, Australia, and South Africa.

The distinguishing features of these primitive rocks are—

(*a*) Their universal extent.
(*b*) Their vast thickness.
(*c*) Their highly metamorphic character.
(*d*) Their poverty in fossils.
(*e*) Their richness in valuable ores and minerals.

The time covered by the formation of the pre-Cambrian systems must have been of extraordinary length, probably as long as the Palæozoic, Mesozoic, and Cainozoic eras put together.

In the Lake Superior region of North America, where the Eozoic has its greatest and perhaps most typical development, the succession recognised by American geologists is as follows, the name Archæan being restricted to the lower highly crystalline complex of altered rocks :—

Pre-Cambrian.

PRE-CAMBRIAN OF NORTH AMERICA.

Algonkian	Keweenawan.	Copper-bearing series.
	Animikian.	Great iron series.
	Huronian.	
	Epalgomian Unconformity.	
Neo-Laurentian	Algomian (Eruptive).	
	Sudburian.	
	Eparchæozoic Unconformity.	
	Laurentian (Eruptive).	
	Keewatin and Coutchiching.	

[1] Gr. *eos*=the dawn, and *zoe*=life.

Archæan.[1]—The greatest and perhaps best known development of rocks of this age occurs in the Laurentian region; but they are well represented in the British Isles, and in all the great continents.

Characteristically they consist of granites, gneisses, and various schists, with which are sometimes associated various clastic and pyroclastic rocks, usually highly altered. No trace of organic remains has ever been found in them, and this circumstance led the geologists of last century to call them *Azoic*,[2] a term at one time loosely applied to all rocks older than the Palæozoic.

The Archæan rocks of the Laurentian region are easily divisible into two great formations, namely, the *Keewatin* schist formation and the *Laurentian* granitic and gneissic complex, which is in some places intrusive in the rocks of the Keewatin, but does not reach into the Huronian.

Keewatin.—The lower Archæan of North America consists mainly of crystalline schists resulting from the metamorphism of igneous rocks that would seem to have been principally surface flows, tuffs, and pyroclastic sediments. Associated with the altered lavas and pyroclastics, there are

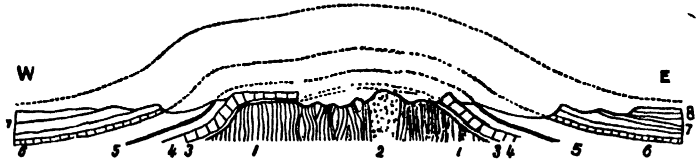


FIG. 199.—Ideal cross-section of Black Hills. (After Henry Newton.)

The vertical scale is about six times the horizontal; the dotted lines indicate the portion of the uplift removed by erosion.

1, Archæan slates and schists.
2, Granite.
3, Cambrian resting unconformably on 1 and 2.
4, Carboniferous.
5, Red beds, with included limestones.
6, Jurassic.
7, Cretaceous.
8, White River Tertiary resting unconformably on 7.

subordinate beds of conglomerate and shale, which are the oldest sedimentary rocks of which there is any record.

Intercalated with the aqueous rocks, there are lenticular beds of jasper and iron ore.

The more abundant metamorphic rocks are hornblende-schist, greenstone-schist, and mica-schist, which are everywhere sharply folded, plicated, and sheared. They have been at many different times intruded by plutonic igneous rocks on a scale not equalled in any other period of the geological record.

The thickness of the Keewatin system amounts to many thousand feet, but the rocks are so complicated with folding, shearing, and intrusives that it is difficult to make a trustworthy estimate.

The massive surface flows and tuffs of which the schists of this period are mainly composed indicate the existence of older rocks below them; and the presence of sedin entary rocks implies denudation and contemporaneous deposition. Of the extent of the pre-Archæan land over which the Keewatin volcanoes spread such vast piles of lavas and tuffs, or of the seas in which the sedimentaries were deposited, nothing whatever is known.

No authentic traces of life have so far been found in the Archæan, and this is perhaps not surprising when we consider the subordinate part played by the sedimentary rocks and the intense metamorphism they have suffered.

[1] Gr. *archaios*=very old. [2] Gr. *a*=without, and *zoe*=life.

Moreover, it is not improbable that the sedimentaries we now see are but the remnants of piles of clastic rocks that were deposited, consolidated, elevated, and destroyed long before the advent of the Palæozoic era. There is nothing to prove that life did not exist in these remote times. On the contrary, the denudation of the dry land by aqueous agencies, and the deposition of sediments, indicate the prevalence of the physical conditions that we usually associate with life.

The earlier pages of historic time are notoriously fragmentary, blurred, or missing; hence it should cause us no surprise to find the first pages of the geological record even more incomplete, dim, and difficult to interpret.

Laurentian.—The rocks of this great system consist of granites and gneisses that have been intruded into the Keewatin as dykes and great bosses, or which occur as the country-rock, covering large areas. At one time the Laurentian was considered to be a distinctively basal granite complex, but wherever it comes in contact with the Keewatin, it is found to be intrusive; hence it must be younger than the Keewatin.

The gneisses include ordinary granite-gneiss, syenite-gneiss, and diorite-

FIG. 200.—Hypothetical section across the Menominee iron region in the vicinity of Quinnesec Valley. (After R. D. Irving, 1890.)

A, Basal sericitic quartz-slates.
B, Quartzite.
C, Limestone.
D, Iron horizon.
E, Slates and quartzites.
G, Granite.
Sch., Schists of the Laurentian.

gneiss, all of which are deeply involved among the granites. Their origin is still obscure. By some writers they are regarded as highly metamorphosed sedimentaries, by others, as foliated and altered eruptives.

The second view is the one most favoured by petrographers.

Algonkian.—This group includes most of the North American pre-Cambrian sedimentaries, many of which are highly metamorphosed, folded, and contorted. It is associated with masses of igneous rock, also much altered and folded.

The rocks are principally conglomerates, sandstones, shales, quartzites, limestones (often graphitic or dolomitic), various schists, gneisses, and granites. Their thickness is probably not less than 40,000 feet.

In the Lake Superior region, where the succession is best seen, the Algonkian may be divided into four distinct systems that are separated by well-marked unconformities—

$$\left.\begin{array}{l}(a)\ \text{Keweenawan}\\(b)\ \text{Upper Huronian}\\(c)\ \text{Middle Huronian}\\(d)\ \text{Lower Huronian}\end{array}\right\}\text{Algonkian.}$$

The largest area covered by the Algonkian is that of the Belt Series of Northern Montana, Idaho, and South British Columbia. Probably of Algonkian age are the schists, granites, etc., appearing in the core of the Black Hills of Dakota (fig. 199).

Fossils have been reported from many places, but in most cases they have been found on close examination to be of inorganic origin. Only in two instances are true fossils known in the pre-Cambrian areas of the United States, namely, in the shales of the Belt Series of Montana, and in the Chuar group of the Grand Canyon. These represent the earliest forms of life yet found.

The fauna of the Algonkian Montana shales includes four species of annelid trails, and trails that appear to have been made by a minute mollusc or crustacean. The same shales also contain thousands of fragments of one or more genera of crustaceans.

The fossils of the Grand Canyon Algonkians are a small discinoid shell and a *Stromatopora*-like hydrozoan.

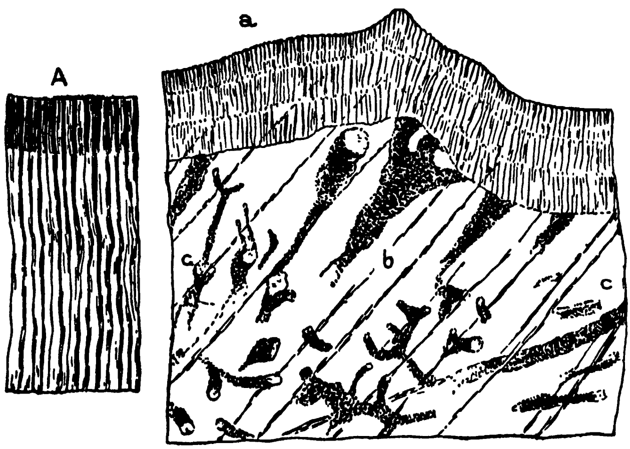


FIG. 201.—*Portion of Eozoon magnified 100 diameters, showing the supposed* original cell-wall with tubulation and the supplemental skeleton with canals. (After W. B. Carpenter.)

(*a*) Original tubulated wall or "Nummuline layer," more magnified in Fig. A.
(*b*, *c*) Intermediate skeleton with canals.

The discovery by Logan in 1863 of certain forms in the Algonkian limestones of Canada and the Adirondacks of New York, which he thought were of organic origin, led to a controversy that lasted nearly forty years. Specimens from the base of the "Grenville limestone" were submitted to J. W. Dawson, who, in 1865, recognised them as organic, and referred them to protozoans related to the foraminifera. On account of their geological position he named them *Eozoon canadense.*

W. B. Carpenter, the microscopist, confirmed the conclusions of Dawson; but William King and T. H. Rowney of Queen's University, Ireland, challenged the organic origin of Eozoon, and affirmed their belief that the imitative structures were purely mineral and of crystalline origin resulting from chemical change.

Similar structures were about this time found in Bavaria and elsewhere. The view of King and Rowney was subsequently supported by Mœbius of Kiel, J. W. Gregory, and H. J. Johnston-Lavis.

It is now generally believed that *Eozoon canadense* is of mineral origin, though some recent writers have revived the organic view.

Pre-Cambrian of other Regions.

Pre-Cambrian rocks represented by numerous isolated patches of granite, gneiss, and crystalline schists are exposed at the surface in all the continents. They form the framework of all the great mountain-chains, and also appear in the truncated arid plateaux of Africa, Asia, and Australia, and in the stumps of some worn-down or sunken chains of great antiquity.

In many regions there is little or no available data as to the age of the rocks. The general practice almost everywhere is to refer all gneissic and schistose rock-formations of unknown age to the Archæan. At the present time the information as to the general character and succession of the pre-Cambrian rocks is so meagre that no satisfactory basis for their correlation with the Eozoic of North America has yet been worked out. A resemblance in some of the broader features is, however, becoming apparent in many instances. The pre-Cambrian of Europe, for example, is characterised by a basal complex of schist, gneiss, and granite, unconformably overlain by a highly altered series that is mainly sedimentary and devoid of recognisable fossils, and is divided by several unconformities. The former may, in a general way, be correlated with the Archæan, and the latter with the Algonkian.

British Isles.—Pre-Cambrian rocks are well exposed in the Highlands of Scotland; and in Donegal, Mayo, and Galway Counties in North and West Ireland. Smaller patches of these rocks crop out in Anglesey; at the Longmynd and the Wrekin in Shropshire; at Malvern Hills and St. David's in Pembrokeshire; and at Charnwood Forest in Leicestershire.

The area occupied by these rocks in Scotland is the largest and most important in the British Isles, and though relatively small when compared with the Eozoic tracts of North America or Scandinavia, there is perhaps no part of Europe where they are so well displayed, or where they have been the subject of more critical examination.

The pre-Cambrian rocks of Scotland comprise four main groups—

4. *Torridonian.*—Mainly sandstones, grits, conglomerates, shales.
3. *Dalradian.*—Gneisses, schists, crystalline limestones, amphibolites, etc.
2. *Moinian.*—Granulitic gneisses and mica-schists.
1. *Lewisian.*—Mainly gneisses (altered igneous rocks), traversed by a varied series of dykes and associated with some schists, cherts, and limestones of sedimentary origin.

Lewisian.—This great system, which may very well be correlated with the Archæan of North America, forms the Isle of Lewis, from which it takes its name, and extends throughout the Outer Hebrides, whence it passes on to the mainland.

The characteristic rocks are gneisses and crystalline schists that are frequently closely folded and contorted, and in places penetrated by numerous igneous dykes.

Generally the rocks are so much altered that it is impossible to make much of their original character; but where they are less altered, they are seen to pass into syenites, diorites, gabbros, and other plutonic igneous rocks.

Moinian.—From the Pentland Firth on the north to nearly the southern edge of the Highlands, and from the great overthrust fault on the west (Zone of Eriboll) to the Tay Valley on the east, most of the Scottish Highlands are composed of siliceous gneisses, the typical rock of which is a granulitic quartz-felspar schist or gneiss. These Moine gneisses rest unconformably on the Lewisian.

Dalradian.—The Southern Highlands of Scotland are composed of a series of schists, gneisses, and crystalline limestones, which form a broad belt from Banff, Aberdeenshire, and Kincardine on the eastern coast to Argyll and the Firth of Clyde on the west. The schists are invaded by granites, diorites, quartz-porphyries, etc. The Dalradian system has been divided into a number of the series, the sequence of which has not been stated with full certainty up to this date. The Dalradian is unconformable to the Moinian.

Torridonian.—The rocks of this system, like the American Algonkian, are typically sedimentary. They often rest on a highly denuded surface of the Lewisian, from which they are separated by a great unconformity, and reach a thickness of 8000 or even 20,000 feet. They are mainly sandstones, grits, flags, which sometimes are interbedded with calcareous bands and shales.

The Torridonian system extends as a belt along the west coast of Scotland

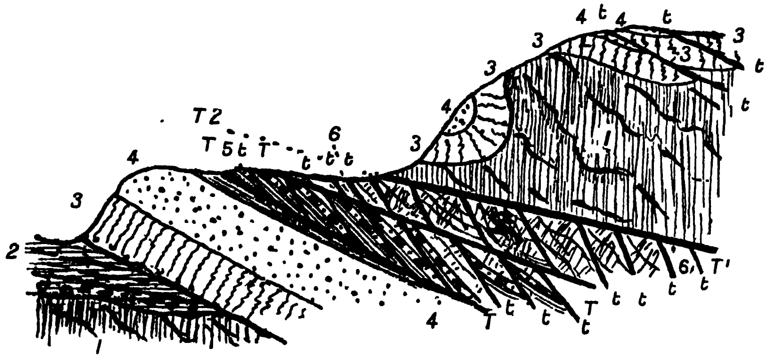


FIG. 202.—Diagrammatic section of west face of Glasven. Hor. dist. = 1½ mile. (After Peach and Horne.)

1, Gneiss covered by Torridon sandstone (2); 3, Cambrian quartzite; 4, Pipe-rock followed by fucoid bed (5), and the limestone (6).

T, T^1, T^2, powerful thrust-planes; t, t, minor thrusts.

for a distance of 100 miles, and takes its name from Lake Torridon, where they are typically displayed. The lowest bed is a conglomerate that contains fragments of Lewisian gneiss, and also pebbles of unaltered igneous rocks that are unknown in the Lewisian of Scotland, but resemble some of the Archæan lavas in Shropshire.

The upper portion of the Torridonian is composed of red and chocolate-coloured sandstones that appear to have been formed in desert or continental conditions.

A characteristic feature of the North-West Highlands of Scotland is the remarkable horizontal shearing of the overlying Cambrian rocks, which have been fractured and deformed by a series of powerful thrust-planes, the most easterly and greatest of which, called the *Moine Thrust*, has carried the strata overlying it westward for a distance of at least ten miles on to the Cambrian rocks (fig. 202).

Pre-Cambrian of other Countries.—The largest continuous tract of pre-Cambrian rocks in Europe occupies Scandinavia, and passes into Finland. The rocks are principally granites, gneisses, and crystalline schists, with which are associated bands of limestone.

The Algonkian and Archæan divisions of the pre-Cambrian are recognised in France; but in Central Europe the rocks have not been subdivided.

Two series of gneisses have been recognised in Northern India; and in China, where there is a great development of gneiss, schists, quartzites, and limestone of pre-Cambrian age, the succession, as worked out by Willis, shows a singular resemblance to that of North America.

In Australia and New Zealand there are extensive tracts occupied by massifs of granite, gneiss, mica-schist, and limestone, frequently much folded and plicated, faulted, and sheared, and in many places intruded by numerous igneous dykes. The age and relationships of these rocks to lower Palæozoic formations have not yet been worked out.

The evidence as to the great antiquity of the rocks reputed to be pre-Cambrian is not always satisfactory, and is only capable of proof where the older Palæozoic formations are present. Detailed geological surveys have, in the past few decades, greatly reduced the areas formerly ascribed to the Archæan, and in all probability future observations will still further reduce their extent.

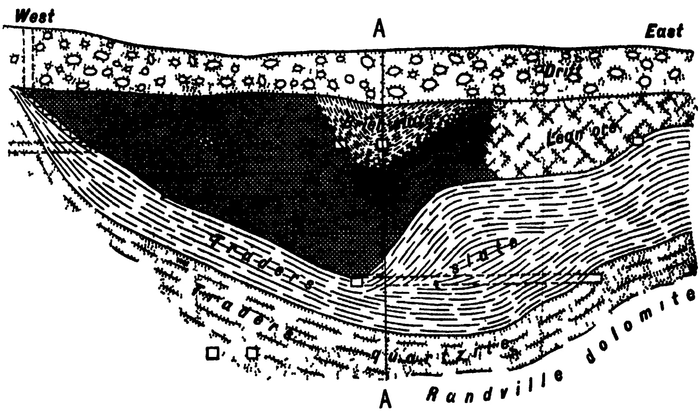


FIG. 203.—Longitudinal section of Loretto Mine, Menominee, Wisconsin.

ECONOMIC MINERALS.

The crystalline rocks of pre-Cambrian age are everywhere remarkable for their richness in metallic ores and precious stones.

The famous copper deposits of Lake Superior, and the vast bodies of iron ore in the same region, occur in the Keweenawan and Huronian divisions of the Algonkian respectively.

The iron ores are of secondary origin, and mostly occur in the trough-like folds of the rocks, as shown in figs. 200 and 203.

Narrow silver-bearing veins of great richness occur in pre-Cambrian conglomerates and greywackes at Cobalt and Porcupine in Ontario.

HISTORY OF THE PRE-CAMBRIAN.

The first pages of the geological record are exceedingly fragmentary, and refer to a time so veiled in obscurity that it is almost impossible to construct a picture of the contemporary physical geography that can claim to be more than a shadowy approximation.

We have already observed that the Archæan is chiefly composed of altered igneous rocks, mostly of intermediate and basic types, with subordinate inter-

calated bands of sedimentaries, among which in most regions calcareous members are conspicuously absent.

Of the land surface on which these piles of Archæan igneous rocks were spread, we have no record of any kind. It may have been a portion of the primitive, wrinkled, and gnarled crust that formed when the globe first cooled down, or a surface composed of sedimentary and igneous rocks spread over the primitive crust. The subject is one that affords ample scope for controversy, and, although full of interest, is, after all, more academic than material. What we do know is that on this ancient land surface, whatever its character and origin, there were poured stupendous floods of lava mingled with piles of fragmentary ejectamenta. The distribution of these Archæan rocks would seem to warrant the belief that the regions in which these titanic outbursts took place already formed the nucleus or framework of the existing continents.

So far as we know, the Archæan rocks were not the product of a single world-wide paroxysmal outburst, but the accumulation of many eruptions, possibly separated by long intervals of comparative quiescence. During the periods of cessation from volcanic activity, the still smoking piles of lavas and ashes became subject to denudation, the detritus being deposited in the adjacent seas, where it afterwards became covered with the ejecta of later eruptions. In this way were formed the bands of conglomerate and shale intercalated among the igneous rocks.

The presumed absence of calcareous bands has been thought by some writers to indicate that the seas of these Archæan times were devoid of lime and other dissolved salts, but of the truth of this we are in complete ignorance.

After an interval of unknown length the lavas and tuffs became invaded by enormous plutonic intrusions of acid magmas, which now constitute the granites and gneisses of the Laurentian.

This was apparently a period of general uplift during which the continents attained a great area, particularly in North America and Western Europe. The beginning of this uplift ends the first or Archæan chapter of the Earth's history, which was mainly characterised, as we have seen, by unparalleled volcanic activity.

The duration of the post-Laurentian uplift is unknown. That it was very great may be gathered from the enormous alteration, folding, and erosion suffered by the Archæan rocks before the Algonkian period began.

The Algonkian is mainly sedimentary, and comprises four great systems separated by unconformities. The systems are a record of subsidence and deposition, and the unconformities a proof of long intervals of uplift and denudation.

The vast thickness of the Algonkian is a witness of prolonged and probably rapid denudation of land-areas long since worn down to a low relief, and covered over with later rock-formations.

The alternating subsidence and uplift, deposition, and denudation resulting in the formation of conglomerates, sandstones, shales, and limestones, now highly altered and deformed, indicate the prevalence of physical conditions in the Algonkian not unlike those of the present day. With such conditions it is not surprising to find many evidences of life; although this truth might have been postulated from the existence of the limestone bands, and the highly organised character of the succeeding Cambrian faunas which it is reasonable to suppose must have been preceded by a long line of ancestors.

CHAPTER XXIII.

PALÆOZOIC ERA.

The Cambrian System.

THE Palæozoic formations have been subdivided on palæontological grounds into six easily recognised systems—

6. Permian.
5. Carboniferous.
4. Devonian.
3. Silurian.
2. Ordovician.
1. Cambrian.

The Palæozoic is the lowest of the three great fossiliferous divisions of sedimentary rocks. It is characterised by the presence of the oldest known organic remains, if we except the few indistinct fossils found in the Algonkian of North America.

The flora is mainly cryptogamic, comprising gigantic ferns, club-mosses, and horse-tails, which in the upper half are associated with conifers and cycads.

The fauna is specially distinguished by its crinoids, corals, graptolites, peculiar brachiopods, ancient nautili, trilobites, and ganoid fishes. Reptiles just appear at the close, and birds and mammals are entirely absent.

The rocks are represented by sandstones, grits, conglomerates, shales, slates, and limestones, frequently tilted, folded, faulted, cleaved, and metamorphosed.

In many places they are intercalated with contemporaneous sheets of lava, and intruded by igneous dykes.

The total thickness of the formations included in the Palæozoic is estimated at 100,000 feet.

In the lower half the Palæozoic contains deposits of gold, silver, tin, and iron ; and in the upper half valuable seams of coal.

When dealing with the Eozoic, in the absence of fossils, we found it impossible to correlate the sandstones of Loch Torridon with those of Longmynd, or the Lewisian gneiss of Scotland with that of Ireland or Anglesey, and still less possible to correlate the ancient rocks of the British Isles with those of Scandinavia or Canada ; but when we reach the fossiliferous Palæozoic formations, all this is changed. The contained fossils enable us to say within narrow limits of error that a certain rock in Great Britain is contemporaneous with such a one in Bohemia, India, Tasmania, or Canada. Moreover, by a careful study of the character of the fossils and of the sediments in which they are embedded, we are able to determine the physical conditions that prevailed simultaneously on the different continents with an approximate degree of certainty.

Relationship of Outcrop to Actual Extent of Formations.—When we say

that a rock-formation or system "occupies," "covers," or "occurs in" a certain tract of country; or when we speak of it as being "well-developed" or "represented" in a specified locality, we refer only to the portion of the formation exposed at the surface. Obviously the portion so exposed may be only a fraction of the total area in which the formation exists, which is only another way of saying that the greater portion of the formation may lie buried beneath younger rocks.

For example, we know that the surface exposures of the Carboniferous Coal-Measures of England cover but a small portion of the area actually occupied by that formation. Bore-holes have proved a great easterly extension into Kent under the overlying Oolite, Greensands, and Chalk; and coal has been discovered at Dover, 1100 feet below the sea, over 100 miles from the nearest outcrop of the Coal-Measures in England.

In the geological map and section shown in fig. 204, we see that the surface exposure of the Cambrian extends only from *b* to *c*, while as a matter of fact that system exists far to the westward of the outcrop below *d* and *e*; and so far as we can see it appears to be co-extensive with the Ordovician and Silurian.

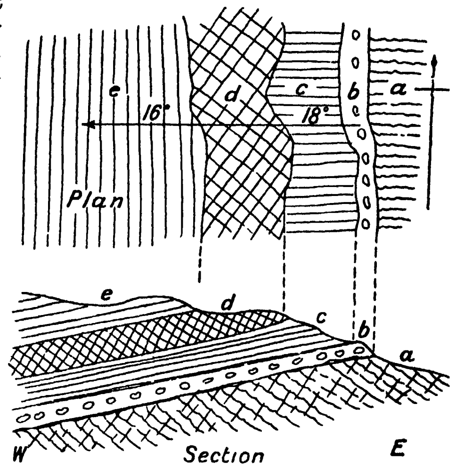


FIG. 204.—Showing relationship of outcrop to actual extent of a rock-formation.
(*a*) Archæan. (*d*) Ordovician.
(*b* and *c*) Cambrian. (*e*) Silurian.

The surface exposure of a rock-formation is usually the result of some accident of folding, tilting, or faulting followed by denudation. Hence a map which shows only the present exposure of a rock-formation conveys no information as to the extent of the sea-floor on which the original sediments were laid down.

CAMBRIAN SYSTEM.

The name *Cambrian* is derived from Cambria, the ancient name of Wales. It was first proposed by Sedgwick in 1833 for a certain group of fossiliferous rocks in North Wales, which subsequent research showed to be Silurian and Ordovician. The name is now confined to the oldest group of Palæozoic fossiliferous strata, and is recognised as a time-name by geologists in all countries.

Distribution.—Cambrian rocks are found in all the continents. They are typically developed in North Wales, where they attain a thickness of 12,000 feet. They are well represented in North Scotland, also in Spain, France, Belgium, Bohemia, and other parts of Central Europe, where their thickness is estimated at 10,000 feet.

In Scandinavia the Cambrian system dwindles down to a few hundred feet of shales and thin-bedded limestones, which indicate deep-water conditions of deposition. Obviously the ancient continent, near which the thicker arenaceous Cambrian rocks of Wales were laid down, existed somewhere to the westward.

The Cambrian rocks in North America occupy a wider extent of country and attain a greater thickness than in any other known part of the globe. They also present a type of sedimentation typically distinct from that of Continental Europe. In the Adirondack Mountains of New York, in East Canada, in the Appalachian Chain, stretching through Pennsylvania, Virginia, Tennessee, Georgia, and Alabama, in Central Nevada, and British Columbia, they are represented by sandstones, shales, and massive beds of limestone that are frequently dolomitic. The thickness of the system in North America varies from 2000 to 10,000 feet. Of a thickness of 7700 feet in Nevada, more than 4000 feet are beds of massive limestones; and in all the States the calcareous members are conspicuous, particularly in the upper divisions of the system.

Cambrian rocks crop out from below later accumulations in the Andes in North-West Argentina, in the Salt Range in India, in Korea, in China, in South-East Australia, and in Tasmania. Cambrian fossils have been found in South Victoria Land.

Rocks.—The rocks of the Cambrian system mainly consist of sandstones, grits, greywackes, shales, slates, and limestones. They are frequently associated with bands of quartzite, quartz-schist, phyllite, and mica-schist.

As might be expected from their great antiquity, the Cambrian rocks are much disturbed. particularly in Great Britain, where they are tilted at high angles, sharply folded and metamorphosed. In Scandinavia and Western Russia they lie comparatively undisturbed over considerable areas.

In England, France, and Belgium the Cambrian rocks are intercalated with sheets of diabase and diabase-tuff, and intruded by dykes of quartz-porphyry and diorite.

In North America the Cambrian rocks are comparatively free from contemporaneous volcanic materials, but in many of the States they are intruded by igneous dykes of later date. The ancient lands of this region were practically base-levelled before the deposition of the Cambrian sediments. This pre-Cambrian plane of marine erosion is one of the most striking features of the epoch. It is well exposed in the Grand Cañon region of Colorado,[1] and has been traced to the Lake district of Canada, where the Cambrian strata are nearly horizontal, and rest on the truncated edges of the earlier schists.[2]

Fauna.—The fauna of the Cambrian System is remarkably rich and varied for rocks of such great antiquity. The lowest forms of life represented are Radiolaria and sponges. Graptolites appear at the close, and the silicified remains of many beautiful jelly-fishes (*Medusæ*) have been described by Walcott from the Lower Cambrian of Eastern New York,[3] of Lugnås, Sweden, of Bohemia and Esthonia, and from the Middle Cambrian of Alabama.

Real corals are absent, and only the *Archæocyathidæ* of doubtful position represent the limestone-building group of coral-like animals. In Europe limestones are scarce, except in a limited area in North-West Scotland, where massive beds of Cambrian limestone are well developed. Crinoids and starfish are very rare.

Annelids, which first made their appearance in the Algonkian, are known to have been numerous, as shown by the plentiful occurrence of their trails and burrows. Specimens of *Salterella* (*Serpulites*) *Maccullochi*, formerly regarded

[1] C. D. Walcott, "Pre-Cambrian Fossiliferous Formations," *Bull. Geol. Soc. Am.*, vol. x., 1899, p. 215.

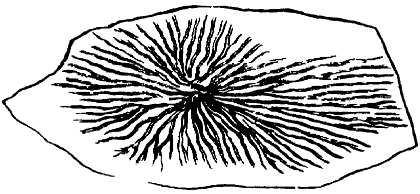
[2] W. G. Wilson, "Geology of the Nipigon Basin," *Geol. Sur. Canada Mem.*, vol. i., 1910, p. 117.

[3] C. D. Walcott, "Fossil Medusæ," *U.S. Geol. Surv. Monograph* xxx., Washington, 1898.

PLATE XIX.

CAMBRIAN FOSSILS.

1. *Oldhamia radiata* (Forb.). Lower Cambrian. Bray Head, Wexford, Ireland.
2. *Oldhamia antiqua* (Forb.). Lower Cambrian. Bray Head, Wexford, Ireland.
3. *Histioderma hibernica* (Kin.). Cast of worm-burrow. Lower Cambrian. Bray Head, Wexford, Ireland.
4. *Histioderma hibernica* (Kin.). Cast of worm-burrow. Lower Cambrian. Bray Head. Showing fine transverse lines.
5. *Hymenocaris vermicauda* (Salt.). Lingula Flags, North Wales.
6. *Paradoxides Davidis* (Salt.). Menevian and Lingula Flags, South Wales
7. *Olenus micrurus* (Salt.). Lingula Flags.
8. *Lingulella Davisii* (M'Coy). Lingula Flags and Tremadoc Slates.



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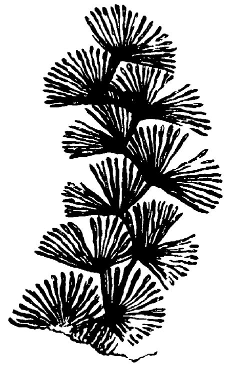

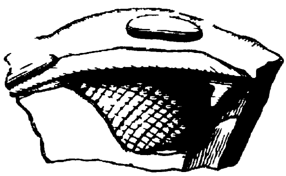

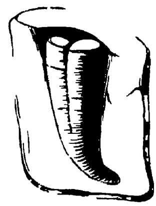

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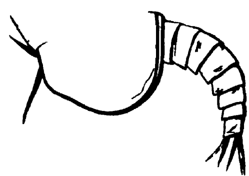

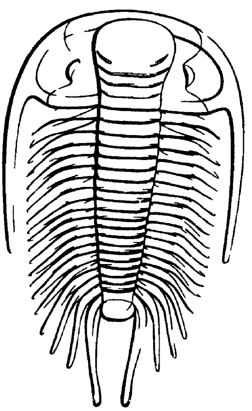

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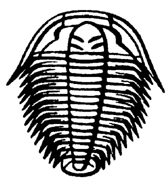

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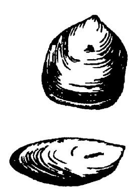

8

CAMBRIAN FOSSILS.

as a tubicolous worm, and now as a pteropod-like organism, are not uncommon in the Lower Cambrian of Scotland and North America.

The most distinctive of the Cambrian fossils are the Crustacea, most of which belong to the extinct trilobites. These exhibit a relatively high state of development, which would point to a long line of ancestors in pre-Cambrian times. Shrimp-like crustaceans appear for the first time in the Upper Cambrian.

Brachiopods of a peculiar type are represented by several hingeless forms, among which *Paterina labradorica* is common. Among other types are *Lingulella* and *Orthis*, which become plentiful in the next period; and of the Mollusca we have numerous Lamellibranchs, Gasteropods, Cephalopods, including *Orthoceras*, and allied forms appear at the end of the Cambrian. Among the Gasteropods we find representatives of the genera *Murchisonia* and *Pleurotomaria*.

No plant remains have yet been found in the Cambrian, though the so-called *fucoid* markings in the Middle Series (Fucoid Beds), in North-West Scotland and elsewhere, have been described as the prints of sea-weeds.

Associated with worm trails there are found in the Cambrian rocks at Bray Head, Wexford, Ireland, peculiar fossil markings, called *Oldhamia*, the organic

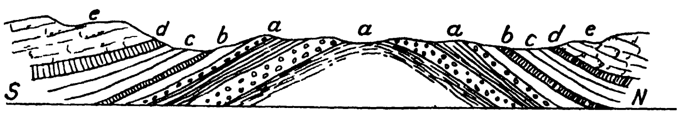

FIG. 205.—Section across Harlech Dome from Cader Idris to Snowdon.

(*a*) Harlech and Llanberis beds.
(*b*) Menevian.
(*c*) Lingula flags.
(*d*) Tremadoc.
(*e*) Ordovician.

nature of which has been doubted. The two species recognised are *O. radiata* and *O. antiqua* (Plate XIX.).

Subdivision of Cambrian.—The Cambrian System has been divided into three main groups of beds, each characterised by its own assemblage of fossils. This threefold subdivision has been identified in Western Europe and North America.

Cambrian	Upper—*Olenus* Beds.
	Middle—*Paradoxides* Beds.
	Lower—*Olenellus* Beds.

The local divisions in England, as seen in the Harlech anticlinal in Western Merionethshire where the succession is complete, are as follows:—

Olenus Beds	4. Tremadoc Slates 3. Lingula Flags	Upper Cambrian.
Paradoxides Beds	2. Menevian Series	Middle Cambrian.
Olenellus Beds	1. Harlech and Llanberis Series	Lower Cambrian.

The three divisions recognised in North America are as under—

Upper Cambrian or *Olenus* Beds	Potsdam Sandstone.
Middle Cambrian or *Paradoxides* Beds	St. John or Acadia Group.
Lower Cambrian or *Olenellus* Beds	Georgia Group.

Olenellus Beds.—These beds are everywhere considered to form the base of the Cambrian System. They contain the oldest fauna of which we have any accurate knowledge. The trilobite *Olenellus* (fig. 206) is characteristic of this series, and hence *Olenellus Beds* and *Lower Cambrian* are synonyms.

At Harlech, in Wales, and in West England, the Lower Cambrian consists mainly of grits interbedded with bands of grey and purple slates; but in North-West Scotland the Cambrian begins with arenaceous deposits and becomes more and more calcareous and dolomitic towards the top, in this showing a curious resemblance to the Cambrian of North America.

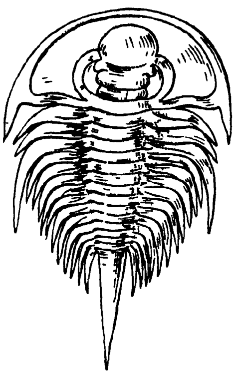

FIG. 206.—*Olenellus.*

Paradoxides Beds.—These constitute the Middle Cambrian and are distinguished by the presence of the trilobite *Paradoxides* (Plate XIX.). In North Wales they consist chiefly of dark slates; and in Canada of slates and shales, with which are correlated the limestones of Central Nevada and British Columbia. A primitive type of the Merostomata, *Sidneyia inexpectans*, occurs in the Middle Cambrian rocks of Mount Wapta, in British Columbia.

Olenus Beds.—In North Wales, this series comprises two groups of beds, the *Lingula Flags* and the *Tremadoc Slates*, the latter forming the closing member of the Cambrian System in Britain (fig. 205).

The *Durness Limestone* which closes the Cambrian System in North-West Scotland contains a fauna unlike any other in the British Isles, comprising a number of species that are unknown in other British areas, but most of which have been identified in the Upper Cambrian *Calciferous Series* of the United States and Canada.

The *Calciferous Series* of North America is approximately the equivalent of the *Tremadoc Slates* of England, with which the upper and perhaps greater portion of the Durness Limestone should also be correlated.

ECONOMIC PRODUCTS.

Cambrian rocks contain veins of gold, silver, and copper, but they have nowhere proved very productive. The most valuable products obtained from this sytem in Great Britain are the roofing slates of the Llanberis Beds in North Wales. They alternate with conglomerates and underlie the Harlech grits. Their colour is bluish-purple; they cleave with ease and regularity, and are probably the finest roofing-slates in the world.

THE HISTORY OF DEPOSITION.

The known exposures of the Cambrian in the different continents form only a small proportion of the area actually occupied by that system, and since the area and distribution of the portions lying buried beneath the younger formations are unknown and cannot be ascertained, we are unable to reconstruct a map that will show even approximately the borders and extent of the seas in which the Cambrian sediments were laid down. Obviously, the same obscurity surrounds the area and distribution of the continents that furnished the sediments.

The fossil fauna even in the most diverse kinds of rock shows a remarkable uniformity throughout both hemispheres, from which we may reasonably

draw the inference that the climatic conditions were fairly uniform throughout the globe during the Cambrian period.

The Cambrian sediments were laid down as marginal deposits around the shores of the then existing continents; and we may infer from the arenaceous character of the material, and the prevalence of worm trails and burrows, that a large proportion of the sediments were deposited in shallow seas. The red and purple colour of many of the Cambrian sandstones, the frequent ripple-marks, sun-cracks, and false-bedding might even suggest that in many instances deposition took place in shallow inland lakes, or in land-locked estuaries.

The palæontological evidence shows that the Lower Cambrian fauna of the North-West Highlands is almost identical with that of the Georgian terrain of North America, but essentially different from the Lower Cambrian fauna of the rest of Europe.

In the case of the Northern Hemisphere, it seems not improbable that the continent which provided the sediments was situated in the North Atlantic region, with long prolongations stretching far to the east and to the west, but separated from the rest of Europe by a deep sea.

Cambrian Glaciation.—In Northern Norway there is a coarse breccia-conglomerate resting on a polished and striated pavement that is believed to be glacial. The glacial beds belong to a series of sedimentary beds known as the Gaisa Beds, regarded by Reusch as equivalent to the Sparagmite formation which underlies rocks containing the *Olenellus* fauna.

Tillite with scratched boulders occurs in the Varanger district of Finmarken, and is referred by Olaf Holtedahl [1] to a pre-Caledonian epoch that may be Cambrian.

A glacial boulder-rock formation containing numerous striated stones has recently been described in the upper Yang-tse Valley, in China,[2] as lying beneath a series of rocks containing Cambrian trilobites.

Cambrian glacial deposits have been described by Howchin [3] and David as occurring in South Australia at intervals over a distance of 460 miles; and Schwarz has reported Cambrian glacial beds in South Africa.

It would appear from these evidences of glaciation that the Archæan rocks must, in Cambrian times, have formed high mountain-chains from which glaciers descended into the sea, where they deposited their load of rocky detritus.

The general facies of the Cambrian life shows that the glaciation was not general, but confined to certain mountain-chains bordering the sea-coasts in some of the continents.

[1] *Am. Jour. Sci.*, vol. xlvii., 1919, p. 85.

[2] Bailey Willis, *Researches in China*, vol. i., part 1, 1907, p. 269.

[3] W. Howchin, "Glacial Beds of Cambrian Age in South Australia," *Quart. Jour. Geol. Soc.*, vol. liv., 1908, p. 234.

CHAPTER XXIV.

ORDOVICIAN SYSTEM.

(Lower Silurian of Murchison.)

THE rocks now recognised as Ordovician are still included in the Lower Silurian by the Geological Survey of Great Britain, which is the position originally assigned to them by Sir Roderick Murchison, who was the first to describe and name the Silurian rocks of Wales. Sedgwick claimed them as part of his Cambrian System ; and to avoid confusion Lapworth, at a later date, suggested placing them in a separate system, to which he gave the name Ordovician after the ancient British tribe Ordovices in whose territory in East Wales and Shropshire the rocks are typically developed. The name has now been generally adopted by geologists.

Relationships.—The Ordovician System, like the Cambrian, has been recognised in all the great continents. It rests conformably on the Cambrian and is conformably overlain by the Silurian, except in places where there is a break in the succession due to one or more of the members of the system being absent.

It will assist us to a better understanding of the relationship of the Cambrian, Ordovician, and Silurian, if we remember that these are closely related systems of conformable strata, laid down on the same sea-floor, and marginal to the same continents. In each region there was a continuance of the same physical conditions of deposition, and though the character of the sediments in many instances indicates frequent oscillations of the land, the general movement was that of subsidence. As a result of uplift in some areas, the continuance of deposition was interrupted for a time, and in such regions we have stratigraphical breaks in the succession, many of them small, others of great magnitude. Of the latter we have a good example in India, where, in the Peninsula and Salt Range, there is a great hiatus between the Cambrian and Permian, arising from a long persistent uplift after the deposition of the Cambrian.

The fauna throughout this gigantic succession of strata is closely related and stamped with the same general facies ; and this is what we should expect to find in sediments laid down in the same continuous sea. In a rich and varied fauna, the dominant and characteristic organisms are trilobites and graptolites.

The threefold subdivision into Cambrian, Ordovician, and Silurian is purely empirical and based on the range of certain well-marked genera. The great thickness of the strata, and the sudden appearance, prevalence, and gradual disappearance of many generations of distinctive genera would lead to the inference that these systems covered a vast period of time of which we can make no trustworthy estimate.

Distribution.—In the British Isles, the Ordovician rocks cover a much larger area than the Cambrian. They occupy a considerable portion of Wales and the Lake District, and are also found in Shropshire, Isle of Man, and Cornwall.

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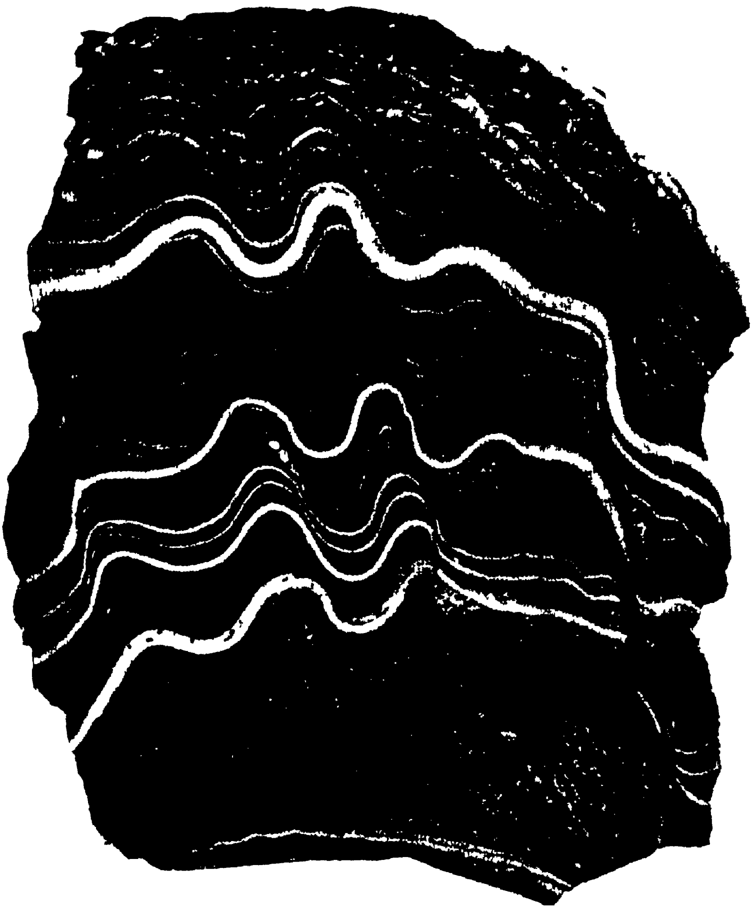
[PLATE XX.

SYNCLINE OF ORDOVICIAN SLATE AT WEST CASTLETON, VERMONT. (After Dale, U. S. Geol. Survey.)



PUCKERED MICA SCHIST FROM TACONIC RANGE.
(After Dale, U.S. Geol. Survey.)

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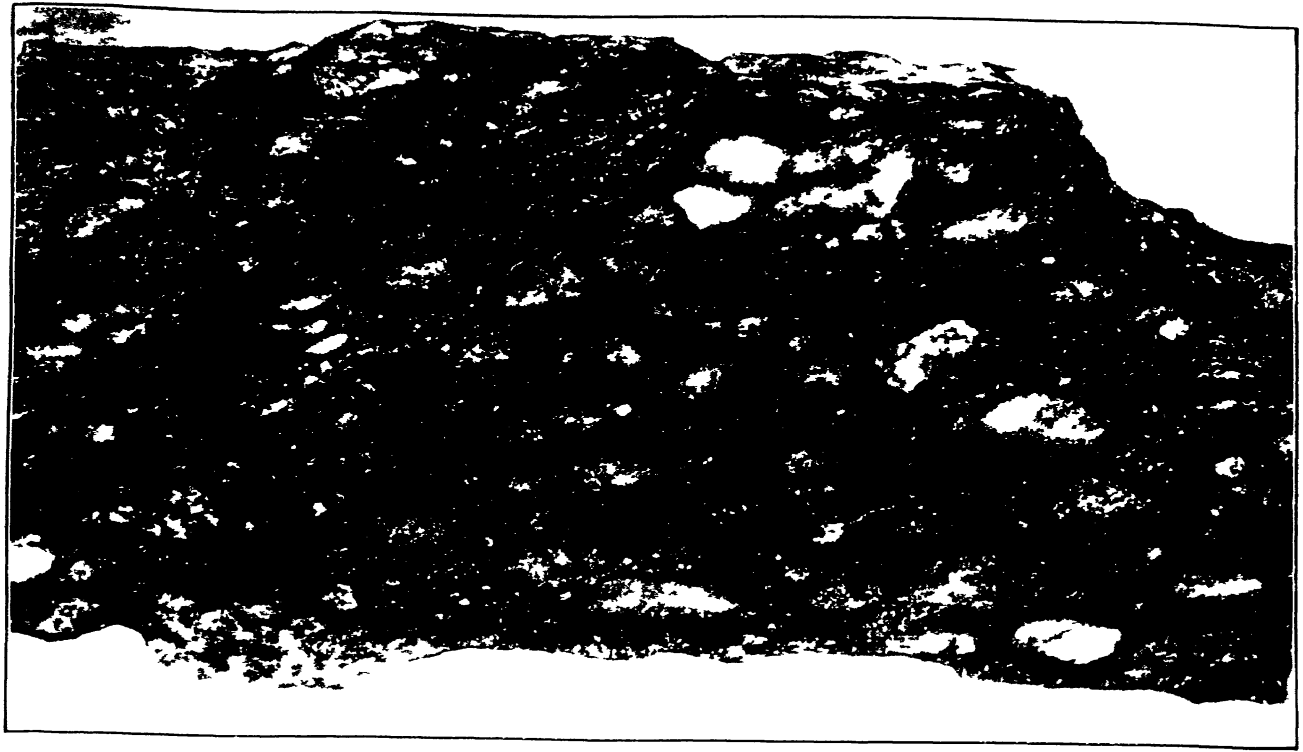


Schist Conglomerate from Felch Mountain District, Michigan. (U. S. Geol. Survey.)

In Scotland they are found in the North-West Highlands, and in the Southern Uplands, where they stretch in a belt from the Firth of Clyde to the Forth. They also occur in South-East Ireland, notably in Ulster, and in Counties Galway and Mayo.

In Continental Europe, Ordovician rocks occupy large areas in Spain, North France, Scandinavia, and the Baltic provinces of former Russia.

The greatest known developments of rocks of this age are found in the United States and Canada, the largest tracts occurring in the Black Hills of South Dakota, in New Mexico, Arizona, California, Utah, Nevada, Wyoming, Montana, Colorado, and further north in British Columbia.

Considerable areas of rocks that have been referred to the Ordovician occur in the Northern Himalayas, in Northern China, central South Siberia, and Arctic regions of Siberia.

The Ordovician System is well represented in the Commonwealth of Australia, notably in the States of Victoria and New South Wales, and also in Western Tasmania and New Zealand. Graptolites were discovered in the South Orkney Islands by Pirie, which would support the view that the older

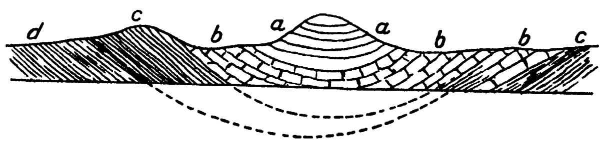


FIG. 207.—Showing structure of Taconic Mountains. (After Walcott.)

(*a*) Hudson shales. (*b*) Trenton, Chazy, and other limestones
(*c*) Cambrian (Potsdam) micaceous shales.
(*d*) Lower Cambrian (Georgian). (*a* and *b*)=Ordovician.

Palæozoic formations are represented in the American quadrant of the Antarctic continent.

Rocks.—In Europe, except in the southern regions, the Ordovician consists mainly of detrital material which composes massive beds of grit, conglomerates, sandstones or quartzites, greywackes, and shales with which are associated subordinate lenses of limestone. The scarcity of calcareous rocks in the Ordovician of Europe is in marked contrast with that of North America, where limestones are conspicuously abundant. It would appear as if the conditions of deposition that prevailed in Europe and North America, in the Cambrian, were continued into the Ordovician. Generally, throughout the United States and Canada, the rocks of that age are limestones, shales, and sandstones, the former always conspicuous and usually richly fossiliferous.

In the central valley of Tennessee, in Cincinnati, Alabama, and many of the neighbouring States, the Ordovician rocks lie horizontal or appear in gentle folds ; but in Vermont (Plate XX.), Eastern Tennessee, West Virginia, and in the mountains of Arkansas they are tilted at high angles. In Wales and England they are tilted at various angles.

In Wales and Shropshire the Ordovician grits, which consist mainly of resorted volcanic debris, are intercalated with thick sheets of lava and tuffs ; and in the Lake District, vast piles of volcanic material dominate the system. In these areas we thus have conclusive proof of intense and prolongated volcanic activity, contemporaneous with the deposition of the fossiliferous Ordovician.

In America there is little evidence of contemporaneous volcanic disturbance, the general tranquillity of the Cambrian having continued into the Silurian.

The relationship of the Ordovician to the Cambrian in the Taconic Mountains is shown in the above figure. Plate XXI. shows a puckered mica-schist.

In a general review of this period, we observe that the Ordovician, like the Cambrian, contains two distinct facies of sediments, an arenaceous and calcareous, the former typically European, the latter typically American.

Fauna.—There was a marked change in the life at the close of the Cambrian, and many genera and species abundant in that system are absent in the Ordovician, in which, however, many new forms appear for the first time.

In a rich and varied fauna graptolites and trilobites are the most important organisms, and of these the graptolites may perhaps be regarded as distinctively Ordovician. They comprise a great many genera and include two-, four-, and many-branched kinds (fig. 211). Among the best known are—

Diplograptus.[1]
Tetragraptus.[2]
Cœnograptus.[3]

Corals and crinoids are numerous in the limestones and calcareous strata; while Brachiopods are well represented by the genera *Orthis*, *Strophomena*, and

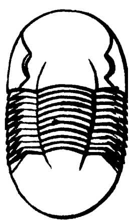


FIG. 208.—*Illænus.*

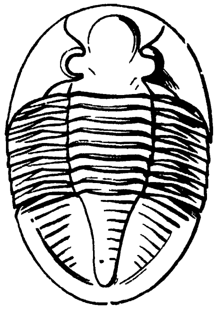


FIG. 209.—*Asaphus.*

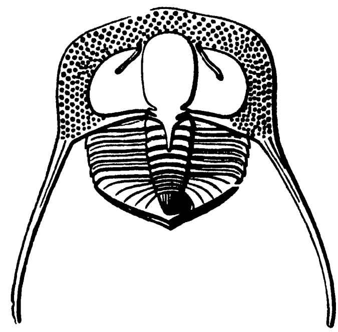


FIG. 210.—*Trinucleus.*

Leptæna, which occur in the arenaceous facies of sediments, together with many Lamellibranchs and Gasteropods. Of Cephalopods we still have the persistent *Orthoceras*,[4] which first appeared in the Cambrian (Plate XXIII.).

The trilobites attain their maximum development in this period, more than half of all the known genera being peculiarly Ordovician. A few, like *Agnostus* and *Calymene*, survived from the Cambrian, while the others appear for the first time. In the Silurian they fall to half the number, and in the succeeding formations dwindle rapidly, till they finally disappear at the close of the Palæozoic.

Among the prominent Ordovician trilobites we find *Agnostus*, *Ogygia*, *Asaphus*, *Trinucleus*, and *Illænus* (Plate XXIV. and figs. 208–210).

The remains of fish-like organisms, the earliest known vertebrates, are found abundantly in the Ordovician of Colorado.

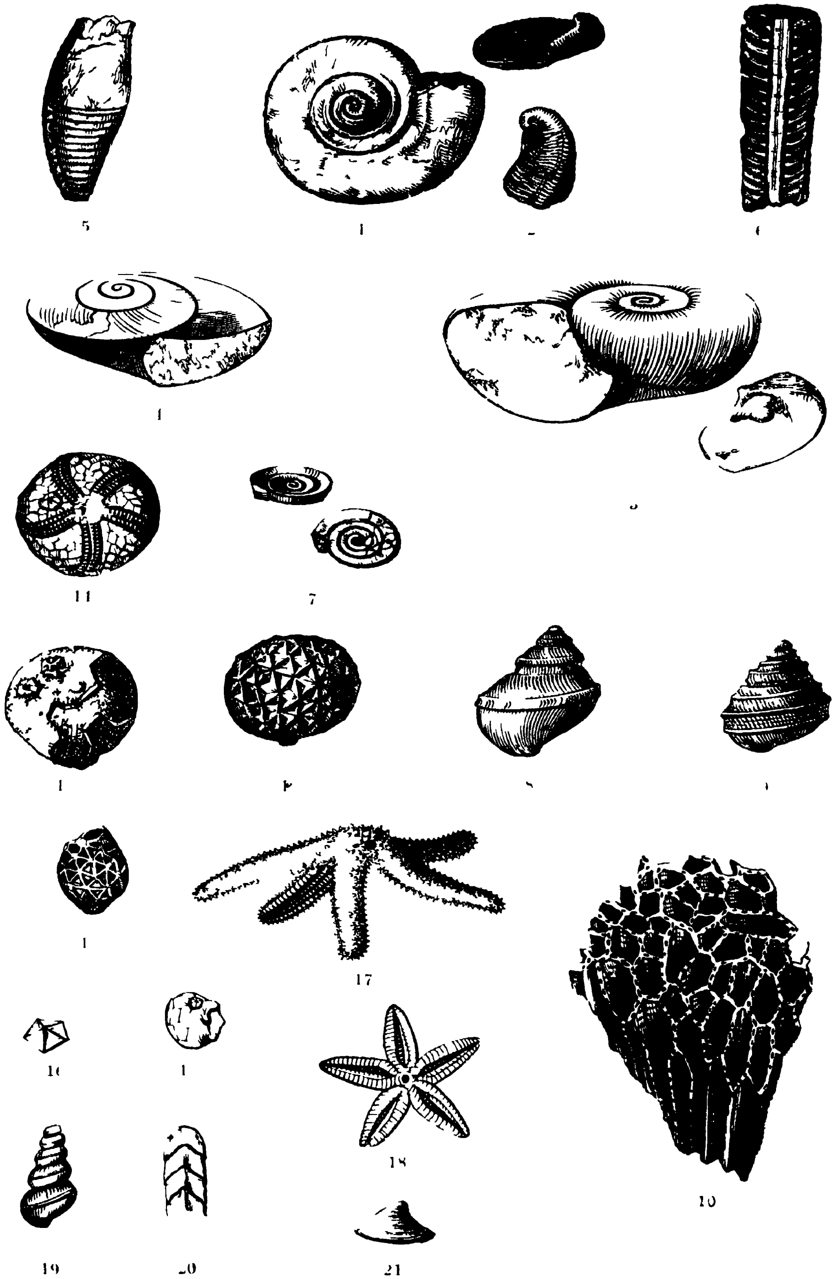
No fossil remains of land plants are known in this period, but at Olonetz, in N.W. Russia, in a series of sandstones and dolomites ascribed to this system, or even the Cambrian, there is a seam of anthracite, the presence of which

[1] Gr. *diplous*=double, and *grapho*=I write (*i.e.* pen).
[2] Gr. *tetra*=four, and *grapho*.
[3] Gr. *koinos*=kindred, and *grapho*.
[4] Gr. *orthos*=straight, and *keras*=a horn.

PLATE XXIII.

ORDOVICIAN FOSSILS.

1. *Maclurea Peachii* (Salt.). Llandeilo of Durness, North-West Highlands.
2. Operculum of *Maclurea Peachii.*
3. *Maclurea Logani* (Salt.) and operculum. Llandeilo of Ayrshire.
4. *Raphistoma æqualis* (Salt.). Bala beds of America.
5. *Oncoceras* sp. (*Cyrtoceras*). Llandeilo of Durness.
6. *Orthoceras mendax* (Salt.). Durness.
7. *Ophileta compacta* (Salt.). Llandeilo of Durness.
8. *Murchisonia sub-rotundata.* Bala beds.
9. *Cyclonema rupestris* (Eichw.). Bala beds.
10. *Halysites catenularia* (Linn.). Chain coral, common in Ordovician and Silurian.
11. *Caryocystites balticus* (Eichw.). Abundant in Llandeilo of South Wales and Scandinavia.
12. *Caryocystites granatum* (Wahl.). Llandeilo and Bala of South Wales and Scandinavia.
13. *Sphæronites punctatus* (Forbes). Bala beds.
14. *Agelacrinites Buchianus* (Forbes). Caradoc, South Wales.
15. *Sphæronites* (*Caryocystites*) *munitus* (Forbes). Bala beds.
16. Ovarium pyramid of *Echinosphærites.*
17. *Palæaster* (*Urasterella ?*) *asperrimus* (Salt.). Bala beds.
18. *Palæaster* (*Stenaster ?*) *obtusus* (Forbes). Bala of Wales and Ireland.
19. *Murchisonia obscura* (Portl.). Caradoc. Ireland.
20. *Helminthochiton Griffithii* (Salt.).
21. *Patella ? Saturni* (*Discina ?*). Llandeilo.



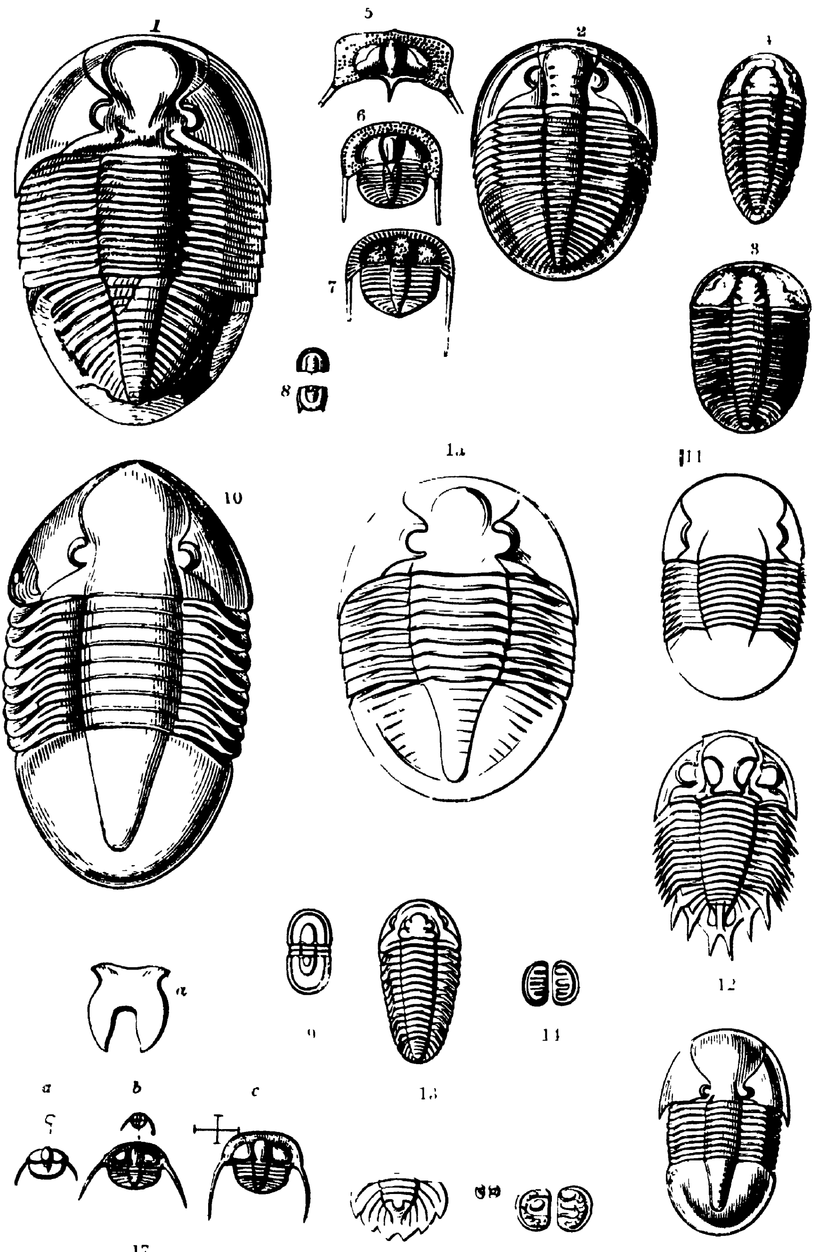
ORDOVICIAN FOSSILS

PLATE XXIV.

ORDOVICIAN FOSSIL CRUSTACEA.

1. *Asaphus tyrannus* (Murch.). Llandeilo rocks.
1*a*. Do. do.
2. *Ogygia Buchii* (Brongn.) Llandeilo Flags
3. *Calymene duplicata* (Murch.) Llandeilo and Caradoc rocks.
4. *Calymene brevicapitata* (Portlock). Ranges from Llandeilo Flags to Wenlock Shale.
5. *Trinucleus concentricus* (Eaton). Caradoc and Llandovery rocks.
6. *Trinucleus Lloydii* (Murch.). Llandeilo and Caradoc.
7. *Trinucleus fimbriatus* (Murch.). Llandeilo and Caradoc.
8. *Agnostus M'Coyi* (Salt.) Llandeilo beds.
9. *Agnostus trinodus* (Salt.). Caradoc.
10. *Asaphus Powisii* and labrum (Murch.) Llandeilo and Caradoc.
11. *Illænus Davisii* (Salt.). Caradoc and Bala
12. *Lichas laxatus* (M'Coy) Caradoc and Llandovery. Ireland.
13. *Calymene* allied to *brevicapitata*. Caradoc.
14. *Beyrichia complicata* (Salt.). Llandeilo and Caradoc.
15. *Beyrichia tuberculata* (Kloden) or *Wilckensiana* Caradoc or Bala.
16. Pygidium of *Lichas Barrandei* ? (Fletch. and Salt.).
17. *Trinucleus concentricus* (Eaton), in three stages of development. (After Barrande).
18. *Stygina latifrons* (Portl.) Caradoc. Ireland. (After Murchison.)

[PLATE XXIV.



ORDOVICIAN FOSSIL CRUSTACEA.

PLATE XXV.

ORDOVICIAN AND SILURIAN FOSSILS.

ORDOVICIAN.

Trilobites.

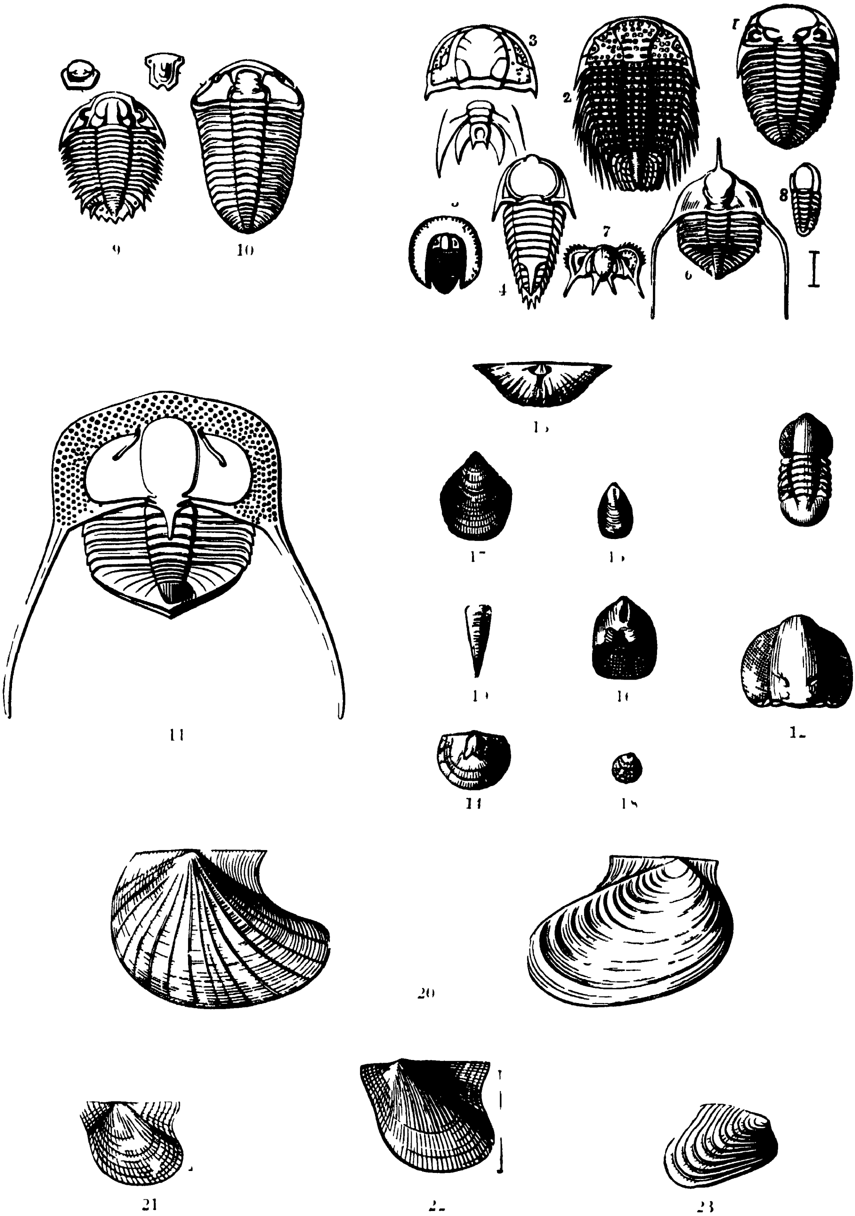
1. *Phacops conophthalmus* (Boeck.). Caradoc Sandstone.
2. *Cybele verrucosa* (Portl.). Caradoc and Lower Llandovery.
3. *Cheirurus clavifrons* (Dalm.). Caradoc.
4. *Remopleurides dorso-spinifer* (Portl.). Caradoc rocks.
5. *Harpes flanagani* (Portl.). Caradoc rocks.
6. *Ampyx nudus* (Murch.). Llandeilo and Caradoc.
7. *Acidaspis bispinosus* (M'Coy). Caradoc rocks.
8. *Cyphoniscus socialis* (Salt.). Caradoc rocks.
9. *Lichas anglicus* (Beyr.). Dudley, etc.
10. *Calymene tuberculata* (Salt.). Kendal. Barrington.
11. *Trinucleus concentricus* (Burm.). Llandeilo and Lower Llandovery.
12. *Æglina mirabilis* (Forb.). Llandeilo and Caradoc.

Brachiopods.

13. *Orthis alata* (Sow.). Arenig rocks.
14. *Orthis striatula* (Linn.). Arenig, Llandeilo and Caradoc.
15. *Lingula attenuata* (Sow.). Arenig, Llandeilo and Caradoc.
16. *Lingula granulata* (Phill.). Llandeilo and Caradoc.
17. *Lingula Ramsayi* (Salt.). Llandeilo.
18. *Siphonotreta micula* (M'Coy). Llandeilo and Caradoc.
19. *Theca reversa* (Salt.) (Pteropod).

SILURIAN.

20. *Avicula Danbyi* (M'Coy). Wenlock and Ludlow.
21. *Pterinea asperula* (M'Coy). Wenlock.
22. *Pterinea tenuistriata* (M'Coy). Wenlock and Ludlow.
23. *Pterinea planulata* (Conr.). Upper Llandovery to Wenlock.



ORDOVICIAN AND SILURIAN FOSSILS

would appear to be evidence of the existence of peat-bogs even in these remote times.

Subdivision: British Isles.—The typical subdivision of the Ordovician as seen in Shropshire is as follows, the oldest being at the bottom:—

Ordovician {
3. Caradoc or Bala Beds—Grits and shales with their bands of limestone (4000 feet).
2. Llandeilo Beds—Black flags, shales, and limestones (3000 feet).
1. Arenig Beds—Black flags, grits, or quartzite (3000 feet).

With these beds there are associated great intercalated masses of lavas, tuffs, and agglomerates.

In the Lake District, where the total thickness is 20,000 feet, more than half of which is volcanic material, the succession is as given below—

4. Ashgill Group.
3. Bala Group—Coniston Limestone (Caradocian).
2. Llandeilo Group—Borrowdale Volcanic Series (10,000 feet).
1. Arenig Group—Skiddaw Slates, upper part (7000 feet).

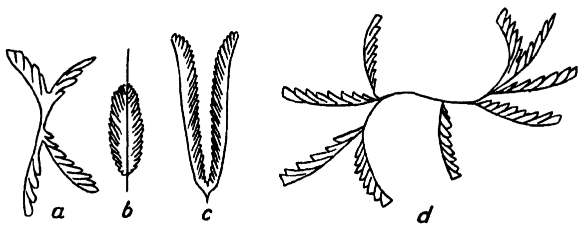


FIG. 211.—Ordovician graptolites.

(a) *Tetragraptus*. (b) *Diplograptus*. (c) *Didymograptus Murchisoni*. (d) *Cœnograptus*.

The Ordovician of England contains a great diversity of deposits, some containing shelly fossils, others graptolites. This has led to the construction of two parallel classifications, one for the shelly facies distinguished by characteristic trilobites, the other for the graptolitic facies, distinguished by dominant graptolites.

	Trilobites.	Graptolites.
Ashgillian	*Trinucleus seticornis*. (Plate XXV). *Cybele verrucosa*. ,, *Cheirurus juvenis*. ,,	*Dicellograptus anceps*. *Diplograptus complanatus*.
Caradocian	*Trinucleus concentricus*. *Phacops apiculatus*. *Asaphus Powisi*.	*Pleurograptus linearis*. *Dicranograptus Clingani*. *Climacograptus Wilsoni*.
Llandeilian	*Trinucleus favus*. *Asaphus tyrannus*. *Ogygia Buchi*.	*Climacograptus peltifer*. *Nemagraptus gracilis*. *Didymograptus Murchisoni*.
Skiddavian or Arenigian	*Trinucleus Gibbsi*. *Placoparia*. *Æglina binodosa*. *Ogygia Selwyni*.	*Didymograptus bifidus*. *Didymograptus hirundo extensus*. *Didymograptus*.

The first two comprise the Upper Ordovician=Caradoc or Bala Group.

Usually the trilobites and graptolites do not occur together in the same beds, except in the Skiddavian.

Graptolite zones were first established in 1879 by Lapworth, whose researches showed that the vertical range of the species of graptolites is comparatively limited. He recognised twenty zones, one in the Upper Cambrian, eight in the Lower Silurian (Ordovician), and eleven in the Upper Silurian. In recent years the list of zones has been greatly extended.

Arenig Group.—This group of rocks derives its name from the Arenig Mountains in North Wales. It consists of dark slates, shales, flags, and sandstones intercalated in the Shropshire area with a considerable quantity of volcanic debris. Many of the highest mountains in Wales, such as Cader Idris, Arenig, Arans, and Berwyns, are composed of these intercalated masses of lava and tuffs.

The most abundant fossils in this group are graptolites, although trilobites are also common. The characterisitc graptolites are *Tetragraptus serra, Didymograptus extensus*, and *D. bifidus*.

In the North of England, where only the upper part of the Skiddaw slates appears to be Ordovician, there is little or no evidence of volcanic activity during Arenig times.

Llandeilo Group.—This group consists of dark-coloured flagstones, sandstones, and shales; all sometimes more or less calcareous. It also contains a bed of limestone with a rich assemblage of fossils, including many trilobites and shells. The graptolites are abundant and best preserved in the shales.

In Shropshire the Llandeilo beds contain many evidences of contemporaneous volcanic activity, and in the Lake District the Skiddaw slates are followed by an enormous accumulation of basic, andesitic, and rhyolitic lavas, tuffs, and agglomerates, to which the name *Borrowdale Series* has been applied. The estimated thickness of this volcanic pile is 10,000 feet.

The alternating hard and soft bands of volcanic rock have given rise under the influence of denudation to the great diversity of surface features which has made the Lake District one of the most attractive and picturesque regions in Britain. Conspicuous among the mountains composed of the volcanic rocks of the Borrowdale series are Scawfell and Helvellyn.

Among the characteristic graptolites of the Llandeilo Group is *Didymograptus Murchisoni*, which is abundant in the lower beds, and having only a limited range, possesses a zonal value. Trilobites are numerous and include *Asaphus tyrannus* (Plate XXIV. fig. 1) in the lower, and *Ogygia Buchii* (Plate XXIV. fig. 2) in the upper portion.

Bala Group.—This group is named after the town of Bala, where two bands of fossiliferous limestone are well exposed. The Caradoc Sandstone in Shropshire is also of the same age, hence the dual name *Bala* or *Caradoc* frequently applied to this group of beds.

The Bala Limestone of Wales is believed to be the horizontal equivalent of the Coniston Limestone of the Lake District.

The most abundant genera of Bala graptolites are *Diplograptus* and *Climacograptus*.

The Bala period was characterised by great volcanic activity, and thick masses of lava and ashes were intercalated with the marine sediments. In many cases the volcanic ash-beds are fossiliferous.

Lying below the *Bala Ash* there is a vast pile of rhyolitic lavas and tuffs which culminates in the peaks of Snowdon, Glyders, and Y-Tryfaen.

Ashgill Group.—This group closes the Ordovician system. It is named after Ashgill in the Lake District. It consists of black shales, limestones, grits, and mudstones. Among the characteristic fossils are *Staurocephalus globiceps, Calymene, Blumenbachi, Homalonotus rudis*, and other trilobites.

Conditions of Ordovician Deposition.—The physical geography of this period

was a continuance of that of the Cambrian; and deposition appears to have taken place in the Northern Hemisphere around the southern shores of a great North Atlantic continent. Intense local volcanic activity prevailed in the Lake District and in Shropshire in England; but elsewhere there appears to have been little or no disturbance. The character of the sediments and contained fauna afford some evidence of minor oscillations of the land, but the general movement was that of subsidence.

North America.—The best recognised subdivisions in North America, where the calcareous facies of sediments predominates, are as follows:—

Cincinnatian or Upper Ordovician	Richmond Beds. Lorraine Beds. Utica Beds.
Mohawkian or Middle Ordovician	Trenton Limestone. Black River Limestone. Lowville Limestone.
Canadian or Lower Ordovician	Chazy Limestone. Beckmantown Limestone.

These three divisions exhibit an approximate parallelism with the Bala, Llandeilo, and Arenig of Great Britain.

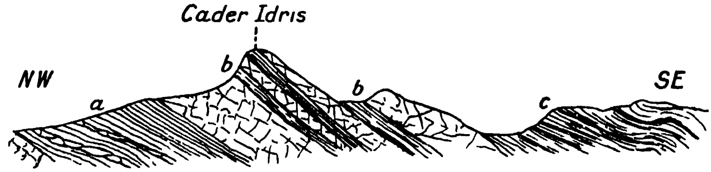


FIG. 212.—Section across Cader Idris. (After Murchison.)

(a) Lingula flags and Tremadoc slates with bands of porphyry.
(b) Massive porphyrites and greenstones, alternating with (c).
(c) Arenig and Llandeilo beds.
(a and b) = Upper Cambrian. (c) = Ordovician.

Australasia.—Ordovician rocks are well developed in South-East Australia, in the States of Victoria and New South Wales. In Victoria, where they are best known, they consist of alternating bands of slates, shales, greywackes, and quartzites that are usually tilted at high angles. Calcareous rocks are absent or but feebly represented. Fossils are abundant, and of these many European species of graptolites have been recognised. The divisions suggested by Hall for the Ordovician of Victoria are as follows:—

Upper Ordovician	4. Darriwil Series.
Lower Ordovician	3. Castlemaine Series. 2. Bendigo Series. 1. Lancefield Series.

The total thickness of these rocks amounts to many thousand feet.

Economic Products.—The economic importance of the Ordovician is considerable. In the United States the Trenton formation constitutes one of the most productive oil and gas horizons. In Central Tennessee the Ordovician limestones contain large deposits of rock-phosphate; and in Wisconsin and the adjoining States of Iowa and Illinois, valuable ores of lead and zinc occur as replacement deposits in cavities in the limestones of this period.

The mineral-bearing value of the Ordovician rocks in Europe is unimportant. In Australia they contain the celebrated gold-bearing *saddle-reefs* of Bendigo, which have already added about £75,000,000 to the wealth of the State of Victoria.

CHAPTER XXV.

SILURIAN (OR GOTLANDIAN) SYSTEM.

(*Upper Silurian of Murchison and British Geological Survey.*)

THE Silurian system as now defined comprises only the Upper Silurian of Murchison, his Lower Silurian being the " Ordovician " of Lapworth, described in the preceding chapter. As a distinctive name for Murchison's " Upper Silurian," De Lapparent [1] has suggested the term *Gotlandian.*

Silurian rocks are typically developed in Shropshire, and in Central and South Wales, the country of the ancient British tribe *Silures.* They were first described by Sir Roderick Murchison, whose " Siluria " embraced what is now known as the Ordovician and Silurian systems.

Distribution.—Besides occurring in Shropshire and Wales, Silurian rocks occupy nearly the whole of the southern portion of the Lake District; while further north they are extensively developed in the Southern Uplands of Scotland, where they stretch as a wide belt from the Mull of Galloway on the south-west coast to St. Abb's Head, near the Firth of Forth.

The continuation of this belt is found across the Irish Sea in West Ireland where it occupies the greater portion of County Down, whence it extends in a south-west direction through the adjoining counties till it eventually disappears beneath the Carboniferous Limestone. There is a patch of Silurian in County Dublin, and many isolated outcrops occur in the provinces of Connaught and Munster.

The Silurian system occupies areas in Scandinavia and Russia, where it forms a wide belt that runs parallel with the Ordovician. It covers large tracts in Western China, Northern India, Burma, New South Wales, Victoria, Tasmania, New Zealand, Brazil, Peru, and Bolivia.

In North America Silurian rocks are typically developed in the Appalachian Mountains of New York, and in the States of Pennsylvania, Ohio, Michigan, Indiana, and Illinois, all bordering the Lake Country. West of the Mississippi, they extend into Missouri and Arkansas. North of the Lakes, the Silurians extend into Ontario and adjoining Provinces of Canada; and a considerable development is found west of Hudson's Bay, and there are local occurrences in Greenland.

Rocks.—The rocks of this system are almost everywhere sandstones, shales, and limestones. The latter are sometimes dolomitic.

In the European and Asiatic regions the Silurian rocks are more or less arenaceous and calcareous, and show a close approach to the calcareous facies which characterises the lower Palæozoic rocks of North America. As a consequence of this new phase of Silurian deposition in Europe, the two facies of life

[1] *Traité de Géologie,* 3rd ed., 1893, p. 748.

—the shelly and graptolitic—so characteristic of the British Ordovician, is not well marked, and in the higher beds is hardly recognisable.

Silurian rocks in all parts of the globe are remarkably free from contemporaneous volcanic material, from which it would appear that a period of general tranquillity followed the close of the Ordovician.

Fauna.—The general facies of the fauna is similar to that of the closely related Ordovician System; and trilobites and graptolites still remain the dominant organisms.

The distinctive Ordovician genera of graptolites are now mostly replaced by the uniserial forms belonging to the *Monograptidæ.*

Corals are still abundant, but the coral-like bryozoans show a marked decline. Crinoids now reached the summit of their development, being so numerous as to form almost the whole of some massive beds of limestone.

Sea-urchins and starfish are represented, especially in the higher beds of the system.

Brachiopods are particularly abundant, and include some new genera, among which we find *Pentamerus*, *Stricklandia*, and *Dayia*. *Spirifers*, a distinctive type of straight-hinged Brachiopod, first appear in the Silurian, but they attain their greatest development in the Devonian and Carboniferous.

The molluscs are still represented by Lamellibranchs, Gasteropods, and Cephalopods; but it should be noted that the large straight *Orthoceras*, which is the chief representative of the Cephalopods in the Cambrian, is now less abundant though still common; while the curved and coiled forms which first appeared in the Ordovician are plentiful, and represented by a great many genera and species.

The trilobites are still represented by *Illænus*, *Calymene*, *Phacops*, and *Homalonotus*; but the new genera that appear are insufficient to balance the losses due to the disappearance of many Ordovician types; and generally throughout this system there is a sensible decline of the trilobites.

The decline of these ancient crustaceans is more than compensated by the advent in the late Silurian of a group of remarkable crustaceans mainly distinguished for their abnormal size. The most characteristic of these are the gigantic *Pterygotus* and great *Eurypterus*. The former attained a length of six feet, while examples of the latter from one foot to a foot and a half are common.

The fish remains found so abundantly in the *Bone Bed* in the Ludlow Series are the earliest British vertebrates.

The Silurian has furnished the first scorpions. Of the land flora and fauna that clothed and peopled the Silurian continents singularly little is known. Many of the Ordovician and Silurian shales are black with diffused anthracite, which probably represents the altered form of land and aquatic plants.

Relationships.—The Silurian is normally conformable to the Ordovician, with which it is usually co-existent; although in some regions in Europe and North America it is absent where the latter is present, and in Northern Canada is present where the Ordovician is missing.

In regions where uplift took place after the close of the Ordovician, the Silurian is missing; and, conversely, where the submergence of some of the continental tracts that had remained dry land since pre-Cambrian times took place, Silurian sediments were deposited in areas in which no Ordovician or Cambrian rock existed.

In many places the Silurian rocks overlap the Ordovician, and rest unconformably on older rocks. This overlap is *landward*, and arises from the

subsidence of low flat shelving coastal lands that permitted a rapid advance of the sea.

In the British Isles the Silurian and the related Ordovician beds are usually tilted and folded, and in the Southern Uplands of Scotland are compressed into numerous isoclinal folds.

In Northern Europe and North America the Silurian rocks are comparatively undisturbed.

Subdivision in the British Isles.—The Silurian system on the borders of Wales, where Murchison first worked out the succession, begins with conglomerates and sandstones—that is, with beach deposits—and these are followed by the deeper water shales and limestones which alternate with one another, the shales being for the most part graptolitic and the limestones shelly.

Towards the top of the system the rocks again become sandy, and as we ascend, the sandstones become redder and brighter, and finally pass into the overlying *Old Red Sandstone* of Devonian age.

In the prevailing life of these three groups of beds we have in Britain the basis of a threefold division of the Silurian System, which, omitting the details, is as follows:—

Lapworth's Classification.	Murchison's Classification.	
Downtonian	Passage Beds into Old Red Sandstone	Ledbury Shales. Downton Sandstone.
	3. Ludlow Series (1800 feet)	Upper Ludlow. Aymestry Limestone. Lower Ludlow Shale.
Salopian	2. Wenlock Series (2000 feet)	Wenlock Limestone. Wenlock Shale. Woolhope Limestone.
Valentian	1. Llandovery Series (1000 to 3000 feet)	Tarannon Shale. Upper Llandovery. Lower Llandovery.

Nowhere are the Silurian rocks so well developed as at Woolhope, near Hereford, where they mantle round the central dome composed of the Upper Llandovery Sandstones, as shown in fig. 213.

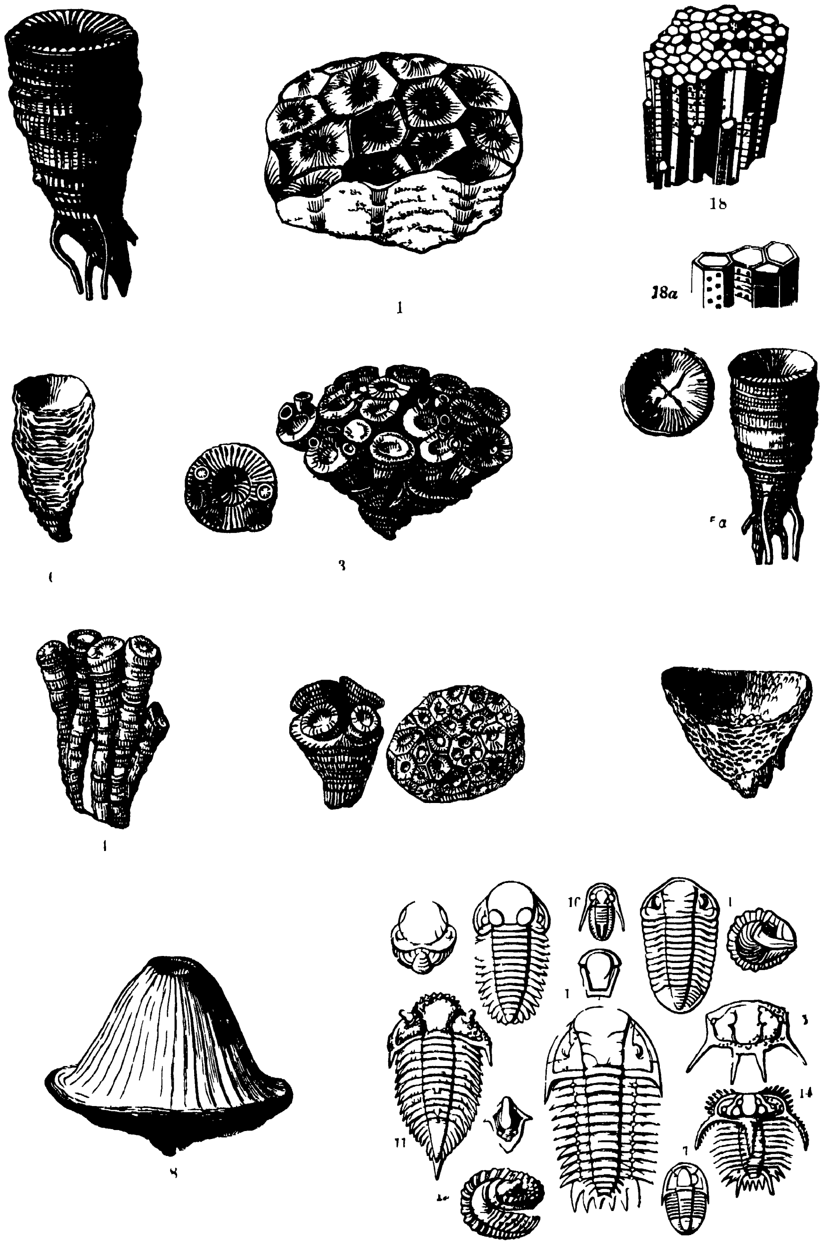
Llandovery Series.—The rocks of this series consist mainly of sandstones and conglomerates, and like all shore-deposits vary greatly in character and thickness. The numerous shells they sometimes contain render them calcareous.

In the Lake District and Moffat in Dumfriesshire, the Llandovery is represented by graptolitic shales, but at Girvan, in Ayrshire, we have the normal conglomerates, sandstones, and limestones.

In some places there is a break at the base of the series, in others, in the middle. Frequently the higher beds overlap the lower, and rest directly on the Ordovician. The breaks arise from minor uplifts, and the overlap from subsidence of a sea-littoral of low relief.

Among the characteristic Brachiopods of the Llandovery beds are the genera *Pentamerus*, *Stricklandia*, and *Meristella*. *Orthis*, *Atrypa*, and *Strophomena* are also present. *Pentamerus undatus* is perhaps the most prevalent species in the lower division, and *P. oblongus* in the upper. Trilobites are also found in these beds.

The Tarannon beds which form the upper member of the Llandovery series consist of soft green and purple slates. They contain few fossils.



SILURIAN FOSSILS

XXVI.

SILURIAN FOSSILS.

1. *Acervularia ananas* (Linn.). Wenlock Limestone.
2. *Arachnophyllum typus* (M'Coy). Wenlock Limestone.

2a. *Arachnophyllum typus* (M'Coy). Showing calicular development or budding from a single corallite.

3. *Cyathophyllum truncatum* (Linn.), and a single cup with its marginal disk-buds atttached. Wenlock Limestone.
4. *Cyathophyllum articulatum* (Wahl.). Wenlock Limestone.
5. *Omphyma turbinatum* (Linn.). Exhibiting the characteristic rootlets springing from the epitheca.

5a. *Omphyma turbinatum* (Linn.) and view of calice, showing the four fossulæ.

6. *Omphyma turbinatum* (Linn.). Cut through to show the tabulæ and arched vesicular wall tissue of the coral.
7. *Cystiphyllum vesiculosum* (Goldf.). Section showing cellular structure.
8. *Ptychophyllum patellatum* (Schloth.). Wenlock Limestone and Shale.
9. *Sphærexochus mirus* (Beyr.). Woolhope and Wenlock rocks.
10. *Cheirurus bimucronatus* (Murch.). Ranges from the Caradoc rocks up to the Aymestry Limestone.
11. *Encrinurus punctatus* (Brünn.). Caradoc to Upper Ludlow.
12. *Encrinurus variolaris* (Brongn.). Wenlock rocks.
13. *Acaste Downingiæ* (Murch.). Upper Llandovery to Upper Ludlow, abundant.
14. *Acidaspis Brightii* (Murch.). Caradoc to Wenlock.
15. *Acidaspis Barrandei* (Fletch. and Salt.). Wenlock Limestone.
16. *Cyphaspis megalops* (M'Coy). Caradoc to Ludlow.
17. *Proetus latifrons* (M'Coy). Upper Llandovery to Wenlock Limestone.
18. *Favosites Gothlandica* (Linn.). Wenlock Limestone.

18a. Enlarged section of corallite, walls showing perforations.

Wenlock Series.—The two bands of limestone in this series are merely local intercalations in the Wenlock Shales. They contain an abundance of well-preserved fossils.

The Wenlock Shales contain several species of graptolites, notably the uniserial *Monograptus*[1] *priodon*, which is a useful zonal form, and *Cyrtograptus*.

Among the most numerous fossils in the calcareous bands are the corals *Halysites*, *Heliolites*, and *Favosites* (Plate XXVI.). Other fossils are the trilobites *Calymene*, *Phacops*, and *Illænus*; the Brachiopods *Atrypa* and *Orthis*; and the Cephalopod *Orthoceras primævum*.

Ludlow Series.—The Lower Ludlow shaly mudstones of this series are more sandy than the underlying Wenlock Shales, and in places contain a graptolitic fauna; in others a shelly. Near Ludlow they contain a number of graptolites, including the characteristic *Monograptus colonus* of zonal value, and *Cyrtograptus*.

The Aymestry Limestone also contains many fossils, including the Brachiopods *Pentamerus* and *Dayia*.

The Upper Ludlow beds are soft grey shales that alternate with thin bands of limestone. Towards the top, where they are sandy, they contain the well-known *Bone Bed*, which is a thin bed full of the bones and spines of fishes together with fragments of the great Eurypterids.

The principal genera of Eurypterida are *Eurypterus*,[2] *Pterygotus*,[3] and *Slimonia*. *Pterygotus anglicus* is the largest known crustacean, and is the *seraphim* of quarrymen.

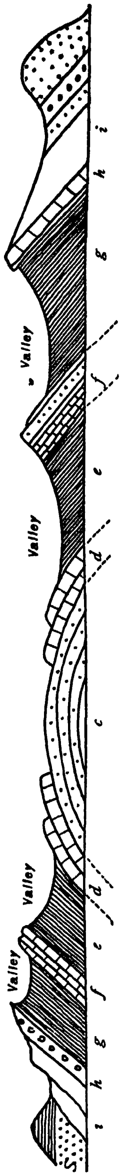


FIG. 213.—Section across Woolhope anticline.

Ludlow. Wenlock. Woolhope Beds. Upper Llandovery. Woolhope Beds. Wenlock. Ludlow. O.R.S.

(c) Upper Llandovery sandstones.
(d) Woolhope beds.
(e) Wenlock shales.
(f) Wenlock limestone.
(g) Lower Ludlow.
(h) Aymestry limestone.
(i) Upper Ludlow.
(O.R.S.) Old Red Sandstone.

North American Divisions. — The three main divisions of the Silurian recognised in North America are as follows:—

Silurian:
- 3. Cayugan Series.
- 2. Niagaran Series.
- 1. Oswegan Series.

The rocks are mainly conglomerates and grits at the base followed by sandstones, shales, limestones, and dolomites. The fauna follows the same general succession as in Western Europe, but an exact parallelism cannot be established between the three main British and North American divisions.

Conditions of Deposition. — At the base of the Salina Series in New York there are lenticular beds of rock-salt varying from 40 to 80 feet thick. These cover an area of nearly 10,000 square miles, and would tend to show that after

[1] Gr. *monos*=single, and *grapho*=I write.
[2] Gr. *eurys*=broad, and *pteron*=a fin.
[3] Gr. *pteryx*=a wing, and *otos*=an ear.

the Niagaran period the general uplift, which seems to have affected the whole of the northern continents after the mid-Silurian, enclosed great shallow lagoons or land-locked seas. The precipitation of the salt would indicate the prevalence of arid climatic conditions at this time.

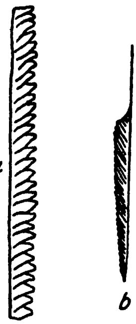


FIG. 214.—Showing uniserial graptolites. (a) *Monograptus priodon* (Bronn). (b) *Monograptus colonus* (Barr.).

This uplift, as we have seen, was universal throughout North America and Northern Europe, and by changing the marine conditions of deposition that prevailed at the close of the mid-Silurian (=Salopian of Europe and Niagaran of North America) to brackish water and lacustrine, it introduced new conditions which led to the advent of the remarkable *Eurypterids*. These belong to a family which made its first appearance in the Cambrian; now they attained a size that would justify the surmise that they lived in a warm climate and possessed a plentiful supply of food.

In North America they are abundant in the *Waterlime Hydraulic Limestone*, the closing beds of the Salina Series.

Eurypterids appeared as suddenly and prominently in the top of the Silurian in Wales, England, Scotland, Sweden, and Russia as in North America, but in these regions there is no association of salt deposits. Nowhere are they associated with marine shells, and they range upward into the *Old Red Sandstone*, in which their associates are land plants and fishes.

Australasia.—Silurian rocks cover large tracts of country in New South Wales, Victoria, and Tasmania. They consist chiefly of sandstones, shales, quartzites, limestones, and cherts, which are frequently sharply tilted and folded. In many places the shales and limestones are richly fossiliferous. The fossils include trilobites, brachiopods, molluscs, corals, and bryozoans.

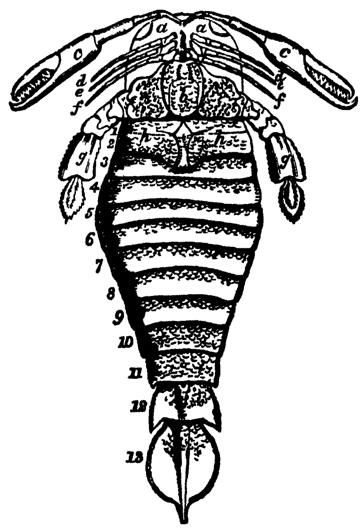


FIG. 215.—*Pterygotus*. (Restored by Dr. H. Woodward.)

For explanation see Plate XXXI.

The celebrated Jenolan caves, to the west of the Blue Mountains in New South Wales, occur in Silurian limestone.

Silurian rocks are present in South-West Tasmania, at Zeehan, and Queen River. They consist of sandstones, slates, and limestones, and contain a marine fauna.

The Silurian System in the South Island of New Zealand is represented by slates, quartzites, cherts, and limestones. Among the fossils in these rocks are numerous trilobites, brachiopods, corals, and bryozoans. Many of the trilobites and brachiopods are almost identical with species characteristic of the Silurian of England and North America, but singularly enough the New Zealand Silurian fauna is quite unlike the Australian. This would tend to show the existence in the Silurian period of a continuous sea-littoral between New Zealand, America, and North-West Europe, and of a deep sea or land barrier between New Zealand and Australia.

It is noticeable that all the known Silurian rocks in the Southern Hemisphere belong to the marine facies. The terrestrial or semi-terrestrial facies,

PLATE XXVII.

SILURIAN FOSSILS.

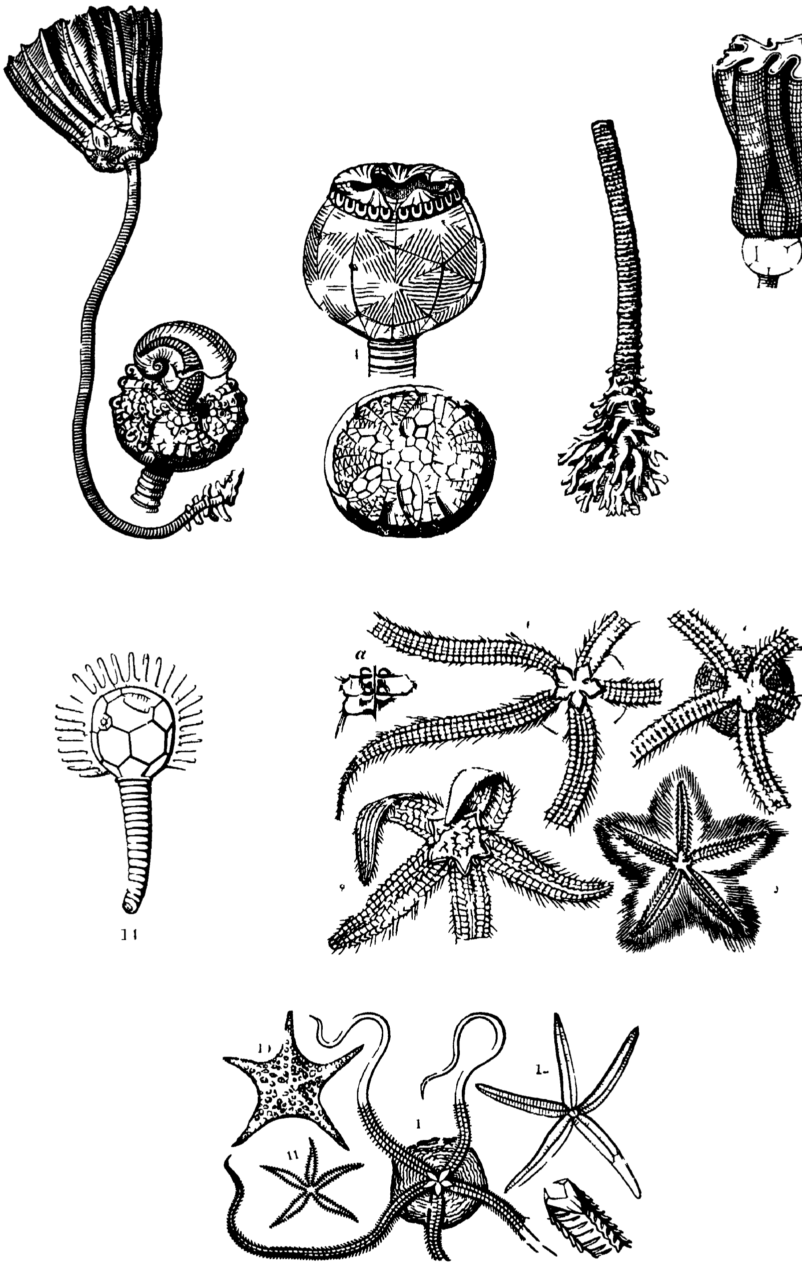
1. *Marsupiocrinus cœlatus* (Phill.). Wenlock Limestone, Dudley, etc.
2. Proboscis of *Marsupiocrinus cœlatus* (Phill.). Inserted in the shell of *Acroculia haliotis* (Sow.). Dudley and Wenlock Edge.
3. *Crotalocrinus rugosus* (Miller). Wenlock Limestone, Dudley, showing the arms above the small pelvis.

3*a*. Stem with rootlets.

4. *Crotalocrinus rugosus* (Miller). Stomach plates removed to show the base of the many-fingered arms. Dudley, etc.
5. The flat stomachal surface, showing branching arms from their bases.
6. *Lapworthura Miltoni* (Salt.). Lower Ludlow rocks. Leintwardine.
7. *Protaster*. Showing base or ventral side.

7*a*. Single ambulacral plates.

8. *Sturtzaster Marstoni* (Salt.). Lower Ludlow rocks. Leintwardine.
9. *Sturtzaster Colvini* (Salt.). Lower Ludlow.
10. *Palasterina primæva* (Forbes). Ludlow rocks.
11. *Urasterella hirundo* (Forbes). Upper Ludlow. Kendal.
12. *Urasterella Ruthveni* (Forbes). Upper Ludlow. Kendal.
13. *Protaster Sedgwickii* (Forbes). Upper Ludlow. Kendal.
14. *Pseudocrinites bifasciatus* (Pearce). Wenlock Limestone, Dudley, etc. After Murchison; *Siluria*, 4th ed.

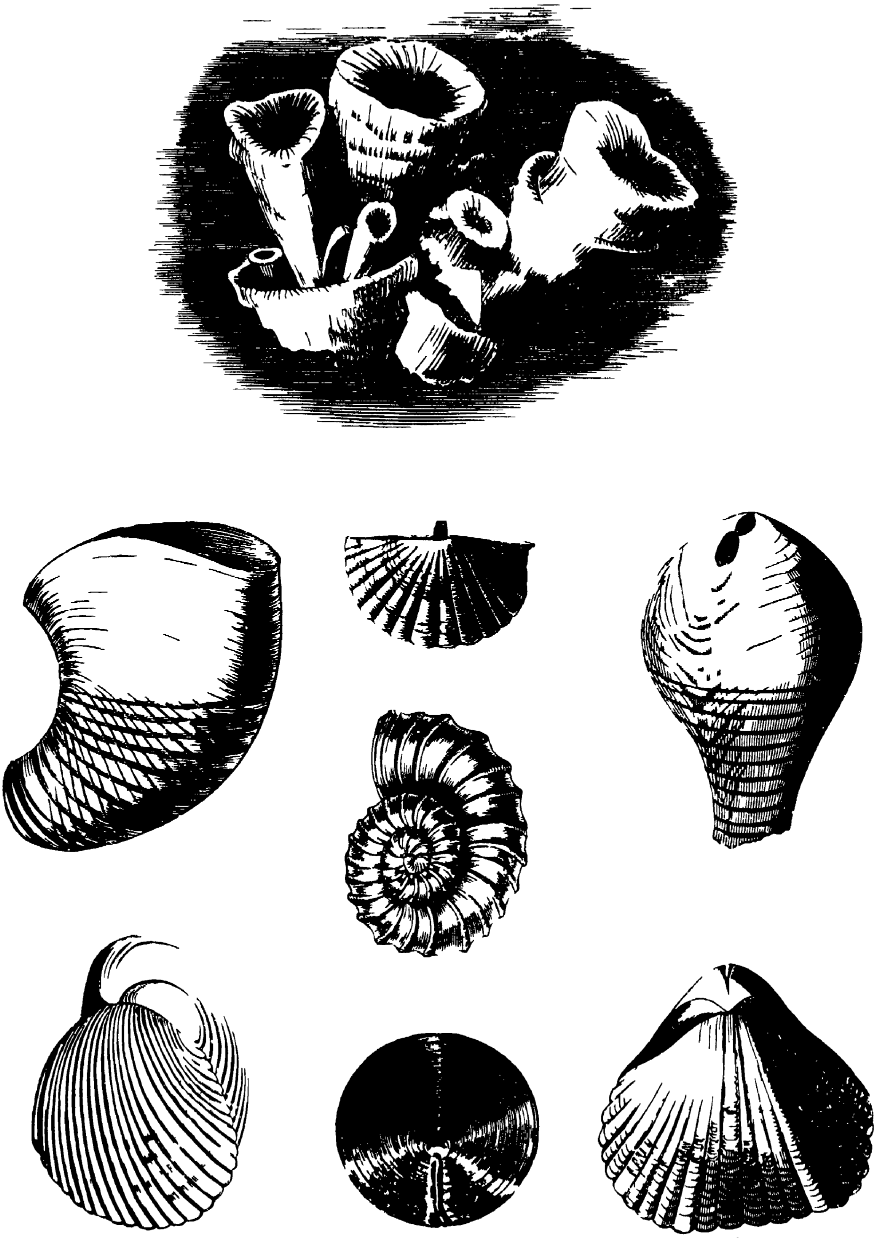


SILURIAN FOSSILS.

PLATE XXVIII.

SILURIAN FOSSILS.

1. *Cyathophyllum truncatum* (Linn.) Upper Silurian. Wenlock Limestone.
2. *Discina Forbesii* (Dav.). Wenlock beds. Dormington, Malvern, etc.
3. *Pentamerus Knightii* (Sow.). Aymestry Limestone. Sedgley, Aymestry, Malvern.
4. *Pentamerus galeatus* (Dalm.). Upper Silurian. Ludlow, Aymestry, Woolhope, Ledbury.
5. *Lituites cornu-arietis* (Sow.). Presteign.
6. *Phragmoceras ventricosum* (Sow.). Upper Silurian. Aymestry, Dudley, etc.
7. *Phragmoceras pyriforme* (Sow.). Upper Silurian. Ledbury, Aymestry, Leintwardine Hill (Ludlow).
8. *Orthis* sp., loc. ?



4

SILURIAN FOSSILS

with its characteristic fauna, which occupies such a conspicuous place in the close of the Silurian in Europe and North America, appears to be missing.

Economic Products.—The limestones of this sytem are valuable as a source of lime and as building-stone. The rock-salt and associated gypsum deposits in the State of New York are of great economic value. Elsewhere the Silurian rocks are not notable for their mineral contents.

Summary.

(1) The lower Palæozoic is divided into three great systems, namely—

3. Silurian.
2. Ordovician.
1. Cambrian.

1. These systems consist of a continuous succession of rocks that are normally conformable to one another. In many wide tracts in Europe and North America all three systems are present, following one another in orderly succession, but in other places there may be considerable breaks in the succession, and a system or portions of a system may be missing. These stratigraphical breaks are due to regional oscillations of the land.

2. The three systems are present in all the continents, and each is divisible into several groups, as follows :—

System.	British Isles.	North America.
Silurian	3. Ludlow Series.	3. Salina.
	2. Wenlock Series.	2. Niagaran.
	1. Llandovery Series.	1. Oswegan.
Ordovician	4 Ashgill Series.	3. Cincinnatian.
	3 Caradoc or Bala.	2. Mohawkian.
	2. Llandeilo.	1. Canadian.
	1. Arenig.	
Cambrian	3 Olenus Beds.	3. Potsdam.
	2. Paradoxides Beds.	2. Acadian.
	1. Olenellus Beds.	1. Georgian.

3. The fauna preserved as fossils in the great pile of sediments comprising the Cambrian, Ordovician, and Silurian shows a closely related facies throughout, as might be expected in the life inhabiting a continuous sea.

4. The life of each system (or period) is dominated by trilobites and (the Ordovician and the Silurian) by graptolites, which appear suddenly in the Cambrian, attain their greatest development in the Ordovician, and begin to wane in the Silurian.

Besides trilobites and graptolites, there is a rich mixed fauna of corals, bryozoans, echinoderms, brachiopods, and molluscs.

5. In Northern Europe and North America, after the mid-Silurian, there began an upward movement which culminated in the *Old Red Sandstone* (Devonian) period. At the close of the Silurian this uplift enclosed great lakes and inland seas, particularly in eastern North America, where the drying up of the enclosed sea-basin led to the formation of valuable deposits of rock-salt.

The brackish-water conditions arising from the uplift led to the advent of a remarkable group of crustaceans, which included among other forms the gigantic *Pterygotus*.

CHAPTER XXVI.

DEVONIAN SYSTEM.

THE name Devonian was first applied by Murchison and Sedgwick to a great succession of greywackes, slates, and limestones occurring in the counties of Devon and Cornwall.

Marine and Lacustrine Types.—The Devonian System is characterised by the presence of two distinct facies of deposits, namely, a *marine* and a *lacustrine*.

The marine type or facies forms continuous sheets of great extent, and is found in all parts of the globe; while the terrestrial, or continental as it is sometimes called, occurs in disconnected areas, and is mostly confined to the British Isles, Western and Northern Europe.

The marine type of deposits was laid down on the floor of seas that were a continuance of the Silurian seas, and the continental type in basins situated in regions where denudation was extremely active.

The marine Devonians comprise the usual succession of sandstones, grits, slates, and limestones, and contain a mixed fauna of trilobites, molluscs, brachiopods, and corals, that do not differ in general character from the fauna of the Silurian. The continental type, on the other hand, consists mainly of brightly coloured red and brown sandstones and marls that contain no brachiopods or corals, but a fauna characterised by the presence of the giant Eurypterids, land plants, and armoured fishes.

The marine facies of rocks is usually called the *Devonian* type, and the continental or lacustrine, the *Old Red Sandstone* type.

Very few fossils are common to the two types, which are nevertheless believed on stratigraphical evidence to be contemporaneous.

In Devon and Cornwall the Devonian succession lies between the Silurian and Carboniferous, and passes conformably into the latter. In France, Belgium, North-West and Central Germany, North Russia, and Southern Europe rocks of Devonian age also lie between the Silurian and Carboniferous.

In Scotland the Old Red Sandstone passes upward into the Carboniferous, and in Wales it passes downward into the Silurian and upward into the Carboniferous.

The stratigraphical evidence would thus seem to show conclusively that the marine Devonian rocks are the equivalent of the continental Old Red Sandstone Series.

Conditions of Deposition.—The differential uplift, which began in the mid-Silurian, continued into the next period; and in Scotland, Ireland, and South Wales, owing to the peculiar configuration of the land, was able to enclose large inland basins in which the deposition of sediments took place contemporaneously with the deposition of sediments in the neighbouring seas.

Most of the basins were completely detached from the sea, but others were

situated near the sea-coasts in situations where minor oscillations of the land sometimes permitted the sea to invade the basins.

As the uplift was differential and faster in Scotland than in the south, the inland basins came into existence in Scotland some time before those in Wales.

The Caledonian Movement.—There is abundant evidence of considerable differential movement in some parts of Western Europe during the early Palæozoic period. In the Southern Uplands of Scotland the Ludlow Series and Passage Beds are absent, while in the North-West Highlands the Silurian is entirely missing.

We may therefore infer that the final folding and ridging up of the Highlands took place after the close of the Ordovician and before the advent of the Carboniferous period; and it first affected the North-West Highlands, and afterwards the Southern Uplands, where, as we have observed, only a portion of the Silurian is absent.

The effects of this folding and differential uplift can be traced in the Lake District, Isle of Man, and North Wales.

This movement or series of movements, usually known as the *Caledonian*, ridged the rocks into a number of approximately parallel folds which run from north-east to south-west. It constitutes one of the dominant structural features of the British Isles, and its effects are at once seen when we examine a geological map of the United Kingdom, for nearly all the boundaries of the older geological formations in Scotland, North-East Ireland, the Lake District, and North Wales have an approximate north-east and south-west bearing. Moreover, the Caledonian folds can be traced into Norway.

These crustal folds produced mountain-chains, of which the present mountains of the Scottish Highlands and Norway are but the worn-down and dissected stumps. At the same time a great tract of land appeared in North-West Europe which played an important part in the subsequent history of the Palæozoic.

Distribution.—In the British Isles the marine Devonian is most fully developed in Cornwall, Devon, and West Somerset.

The old Red Sandstone occupies a triangular area in South Wales, north-west of the Severn. It also occurs in the Cheviot Hills; and further north forms a broad belt which runs across the island from the Firth of Clyde to the Forfar Coast. A considerable tract occurs around the Moray Firth, and practically the whole of the county of Caithness and the Orkney Islands is occupied by the Old Red Sandstone.

In North Ireland the Old Red Sandstone is well developed in the counties of Tyrone and Fermanagh, and in South-West Ireland it forms the greater portion of the mountains of the province of Munster, and occupies nearly all the south-west corner of the island.

In Central Europe only the marine Devonian facies is represented. A large tract of these rocks extends from the north of France, through the broken and wooded Ardennes to the south of Belgium, and thence into Rhenish Prussia, Westphalia, and Nassau. They even pass as far east as the Harz Mountains and Thuringia.

In Southern Europe the Devonian covers a considerable area in Spain and Portugal.

In Russia it occupies an area many thousand square miles in extent, and stretches from Kurland through Livonia to the White Sea. The Old Red facies appears in the Baltic provinces of Russia and in the Dniester basin. There is also a wide development in the Urals, Siberia, Altai Mountains, South-West China, Asia Minor, and Turkish Bosphorus.

The Devonian rocks also cover large tracts in North and South Africa. In South Africa the rocks of this age, known as the *Cape System*, play an important part in the structure of Cape Colony and Natal.

No rocks of Devonian age have so far been recognised in India, but in Australia the marine type occupies extensive tracts in Queensland, New South Wales, Victoria, and Western Australia.

In North America the Devonians are well represented in the Appalachian Mountains of New York, in the States bordering the Great Lakes, in Ontario and Nova Scotia, in Arizona, Colorado, Utah, Nevada, Wyoming, Montana, North and South California, and many parts of Alaska.

Rocks.—The rocks of the marine or Devonian facies are mostly sandstones, conglomerates, grits, shales or slates, and limestones; and of the Old Red Sandstone type, red and brown sandstones, and marls.

The total thickness of the English Devonian is about 8000 feet, and of that of Central Europe 20,000 feet.

The Devonian was generally a period of comparative tranquillity except in Great Britain and Central Europe.

In Scotland the Old Red Sandstone is intercalated with vast masses of andesitic lavas, tuffs, and agglomerates, from which we gather that the continental movement was in Britain accompanied by intense local volcanic activity. The volcanic outbursts took place during the first half of the Old Red Sandstone period. The greatest eruptions occurred in the Cheviot Hills and in the Midland Valley, which stretches across the country from the north-east to south-west between the Highlands and the Southern Uplands. In this region the hard masses of lava and agglomerate stand up as conspicuous ridges, as in the Ochil and Sidlaw Hills. The aggregate thickness of the igneous rocks in Scotland is believed to be about 6000 feet.

In Germany and Devon the marine Devonians contain a large proportion of igneous material, mostly diabase and diabase tuffs. These rocks occur in many separate horizons, showing that the eruptions were separated by intervals of rest.

Fauna.—The general character of the Devonian marine fauna is similar to that of the Silurian, and many of the characteristic Silurian genera still survive.

Graptolites are entirely absent, the last of them being seen in the Ludlow Beds.

Corals and crinoids are still abundant, but the former show a marked decrease as compared with the Silurian.

Brachiopods are numerous, and represented by the genera *Spirifer* (Plate XXIX.), *Rhynchonella*, *Atrypa* (Plate XXIX.), *Chonetes*, *Stringocephalus* (Plate XXIX.), and *Uncites*, the last two being limited to the Devonian. *Productus* appears for the first time.

Molluscs are still abundant, although the gasteropods now occupy a subordinate place; while the cephalopods show a notable advance, being represented by many old forms and a new type, the lobate-sutured *Goniatites*.

The trilobites show a decline in England both in number of genera and species, and those that survive exhibit a tendency to develop into the spiny, highly ornamental forms that are regarded as degenerate types of Crustacea.

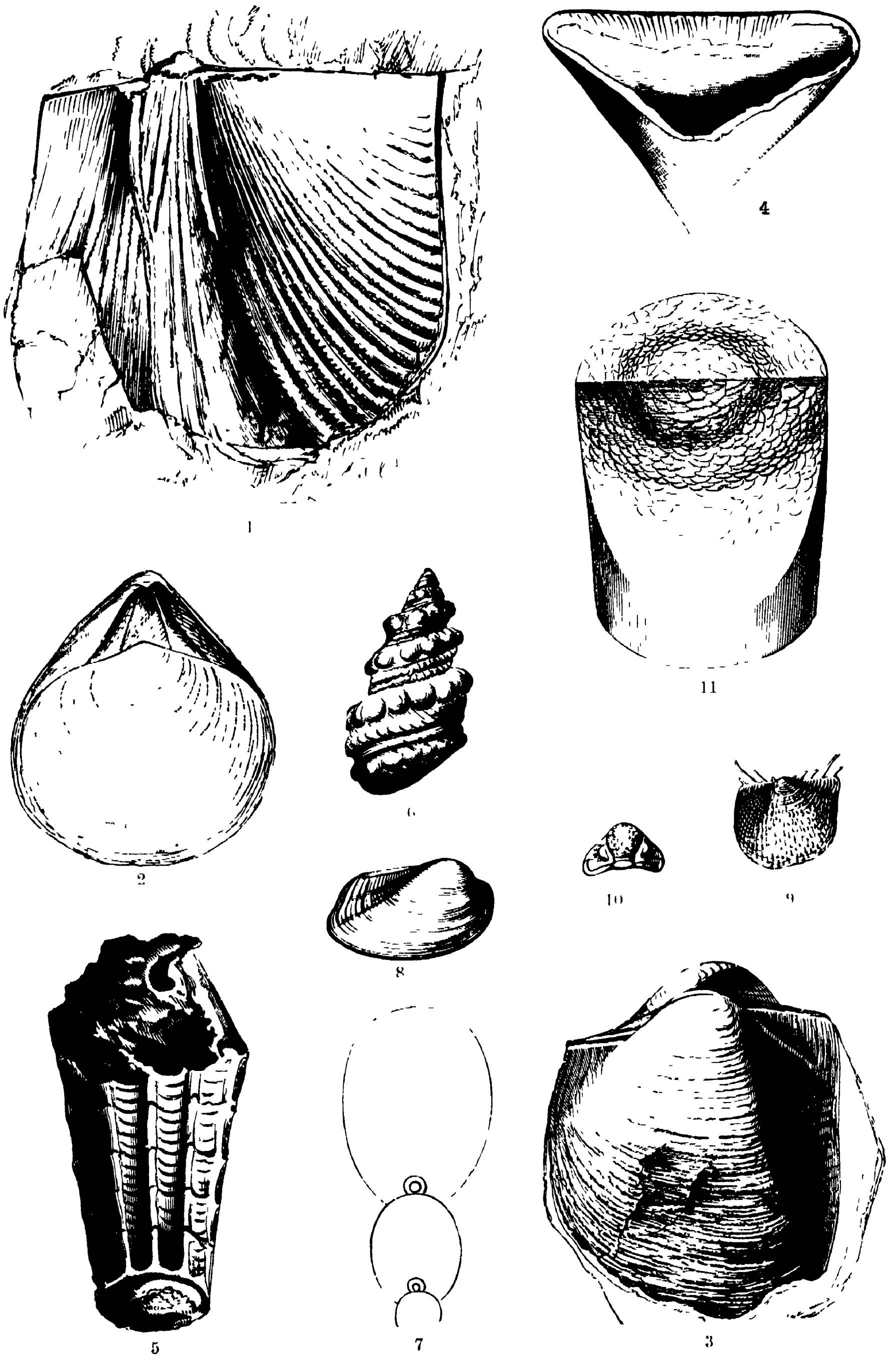
In North America the trilobites present a notable increase over the number of species appearing in the same region in the Silurian epoch, but, as in England, the ornamental forms are conspicuous.

The Old Red Sandstone rocks contain very few fossils, but in a few places

PLATE XXIX.

DEVONIAN FOSSILS.

1. *Spirifer disjunctus* (Sow.). Middle and Upper Devonian. British and Foreign.
2. *Stringocephalus Burtini* (Defr.). Middle Devonian.
3. *Cucullæa trapezium* (Sow.). Middle and Upper Devonian.
4. *Calceola sandalina* (Lam.). Middle Devonian.
5. *Cyrtoceras tridecimale* (Phill.). Middle Devonian.
6. *Murchisonia spinosa* (Phill.). Middle Devonian.
7. Section of *Clymenia lævigata* (Munst.), showing position of siphuncle at base of chamber.
8. *Cucullæa Hardingii* (Sow.). Middle and Upper Devonian.
9. *Strophalosia productoides* (Murch.). Middle and Upper Devonian.
10. Head of *Phacops granulatus* (Munst.). Upper Devonian.
11. *Cystiphyllum vesiculosum* (Goldf.). Coral, and characteristic of the Middle Devonian. The specimen has been cut transversely and obliquely to show the vesicular structure of the interior. (After Phillips.)



DEVONIAN FOSSILS.

in Scotland the giant *Eurypterus* and *Pterygotus* are found in great abundance associated with the remains of land-plants and fishes.

Many of the fishes are protected with large bony plates that form a more or less rigid coat of armour. Among the genera so protected are *Pterichthys*, *Cephalaspis*, and *Coccosteus*.

The plants are principally Lycopods and ferns, which are represented by the genera, *Knorria* and *Palæopteris*.

The Old Red Sandstone also contains a freshwater mussel, *Anodonta Jukesii* (Plate XXXI. fig. 4), which closely resembles living species.

Subdivisions: British Isles.—The marine Devonian rocks of North Devon are divided into eight groups of beds as follows:—

Upper Devonian	8. Pilton Beds. 7. Baggy Beds. 6. Pickwell Down Sandstone.
Middle Devonian	5. Morte Slates. 4. Ilfracombe Beds.
Lower Devonian	3. Hangman Grits. 2. Lynton Slates. 1. Foreland Sandstone.

The strata are so much disturbed by folding and faulting that there is still some doubt as to the correct order of succession of the beds.

Fossils are numerous in the limestones, scarce in the slates, and usually absent in the sandstones. The limestones and slates are marine and the sandstones probably estuarine.

Perhaps some of the sandstones were formed in brackish-water basins near the sea in conditions not dissimilar to those in which some portions of the Old Red Sandstone were laid down.

In the Pickwell Down Sandstone beds, which are red and purple in colour, there are found the remains of fishes and land plants. A few of the fishes are characteristic of the Old Red Sandstone, the commonest genus being *Pteraspis*, which first appeared in the Upper Ludlow towards the close of the Silurian.

The weight of the evidence would seem to support the view that the conditions of deposition of the Pickwell Down Sandstone were related to those of the Mediterranean type.

In Scotland the Old Red Sandstone is divided into two groups, an Upper and a Lower Series, which are separated by a well-marked unconformity, but it should be noted that recent research tends to show that a portion of the Lower Series may belong to the Silurian, and a portion of the Upper Series to the Carboniferous. It would seem from this that the Old Red Sandstone conditions appeared in Scotland earlier than in South Wales, and ended later; and this is what we should look for, since the uplift, which we know began after the mid-Silurian, was differential, being faster in North Britain than in England. As a natural consequence of this the terrestrial or continental conditions of deposition would obviously come into existence in the north sooner than in the south.

From the evidence before us we are led to infer that, as the uplift progressed, the sea retreated southward from the Caledonian region until it reached the ancient coasts of Devon, on the borders of which was formed a land-locked basin to which the sea had occasional access, and in which the Pickwell Down Sandstone was laid down.

The uplift had now reached its climax and was soon followed by subsidence which lasted until the basal limestones of the Carboniferous System were laid

down. As the downward movement progressed, the sea advanced northward, and deposition of sediments began long before deposition could commence in the north. Obviously, then, the beds of the Lower Carboniferous laid down in the Devonian seas would be missing in the north.

Devonian rocks are more fully developed in Rhenish Prussia than elsewhere in Europe. They are arranged in a series of reversed folds, and their estimated thickness is 20,000 feet.

The Lower Devonian of this region consists mainly of sandy and clayey beds in which fossils are not abundant, the most common being brachiopods, among which the characteristic species are *Spirifer auriculatus*, *S. curvatus*, *S. paradoxus*, and *Chonetes dilatata*.

The Middle Devonian is mainly calcareous, and contains in the well-known *Calceola Beds* the rich fauna for which the Devonian of the Eifel has become so famous. Among the typical forms are the brachiopod *Stringocephalus Burtini* (Plate XXX. fig. 7) and the lamellibranch *Megalodon cucullatus* (Plate XXX. fig. 9); the gasteropods *Murchisonia bilineata* and *Pleurotomaria delphinuloides*; and the cephalopods *Orthoceras triangulare* and *Goniatites gracilis*.

The Upper Devonian is chiefly represented by calcareous slates and limestones rich in fossils. Among the brachiopods are *Rhynchonella cuboides*, *Spirifer Verneuili*, and *Productus subaculeatus*. The ammonoid Cephalopod *Clymenia* is entirely limited to the Upper Devonian.

North America.—The threefold division of the Devonian System recognised in North America is as follows:—

Upper Devonian (4000 to 8000 feet)	Chautauquan. Senecan.
Middle Devonian (1000 to 4500 feet)	Erian. Ulsterian.
Lower Devonian (300 to 2000 feet)	Oriskanian. Helderbergian.

By some American writers the Helderbergian limestones are referred to the Upper Silurian.

The North American Devonian rocks are mostly sandstones, conglomerates, shales, quartzites, and limestones. The shales, limestones, and many of the sandstones are marine. Some of the red sandstones, red shales, and conglomerates are estuarine or lacustrine. The Catskill Beds of New York and Pennsylvania, which represent the whole of the Upper Devonian, belong to the continental facies of rocks. They contain only a few freshwater and brackish-water forms.

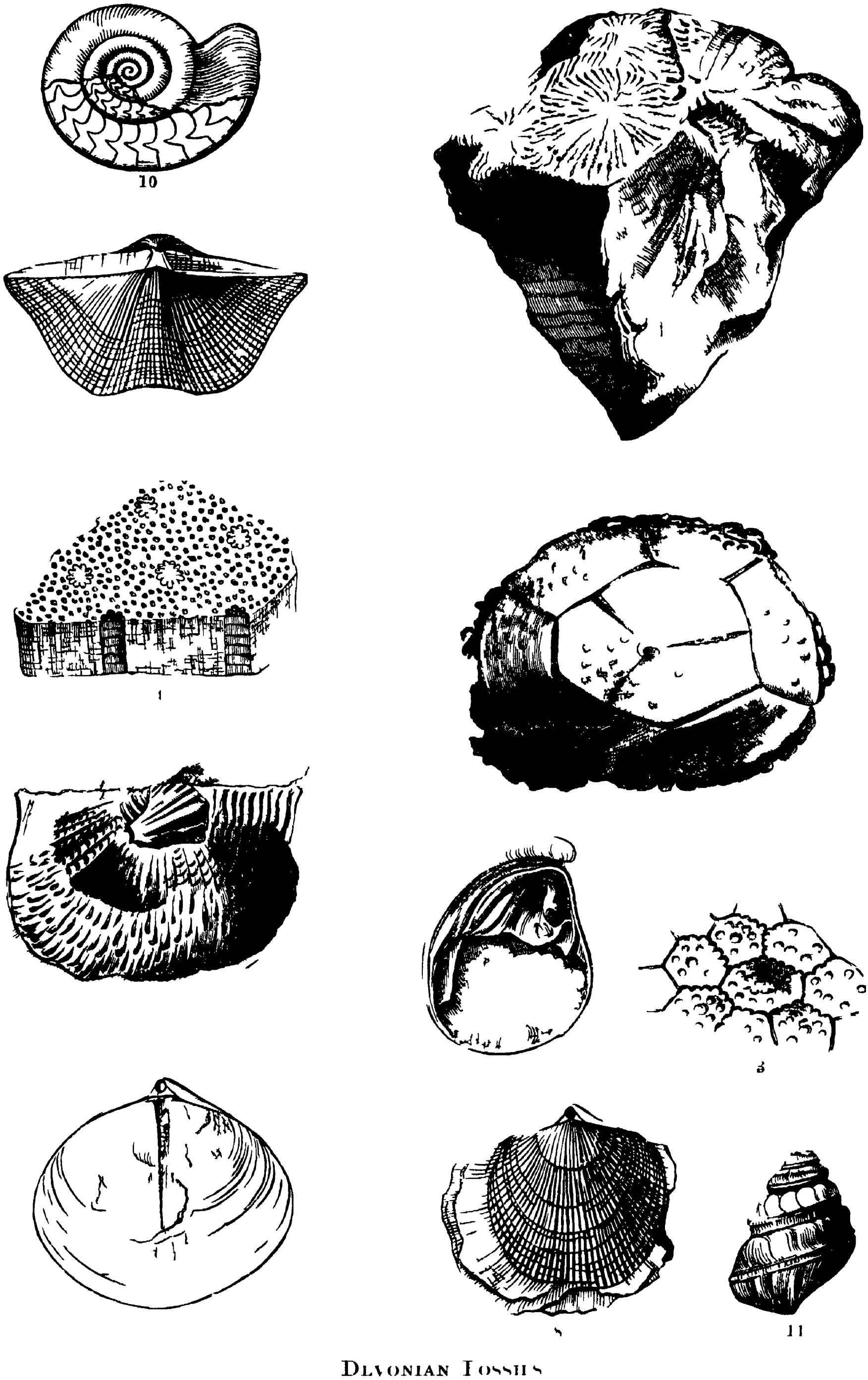
The marine faunas possess the same general features as the European, but, unlike the European, are distinguished by a remarkable revival of the trilobites.

Economic Products.—The Upper Devonian is the chief source of the oil and gas in Pennsylvania and South-West New York, while the Middle Devonian is the oil-bearing series in Ontario. The Devonian shales of Central Tennessee contain valuable deposits of rock-phosphates. In Europe and the other continents the Devonian does not contain many ores or minerals of much economic value.

PLATE XXX.

DEVONIAN FOSSILS.

1. *Stromatopora concentrica* (Goldf.). Middle Devonian. South Devon.
2. *Hexacrinus interscapularis* (Phill.). Middle Devonian. South Devon (basal plates)
3. Apex of *Hexacrinus interscapularis*.
4. *Heliolites porosus* (Goldf.). Middle Devonian. South Devon.
5. *Spirifer disjunctus* (Sow.). Upper Devonian. North and South Devon—*passim.*
6. *Strophalosia productoides* (Murch.). Middle and Upper Devonian.
7. *Stringocephalus Burtini* (Defr.). Middle Devonian. North and South Devon.
8. *Atrypa desquamata* (Sow.). Lower and Middle Devonian. North and South Devon.
9. *Megalodon cucullatus* (Sow.). Middle Devonian. South Devon.
10. *Clymenia undulata* (Munst.). Middle Devonian. South Devon.
11. *Murchisonia bigranulosa* (D'Arch.). Middle Devonian. South Devon.

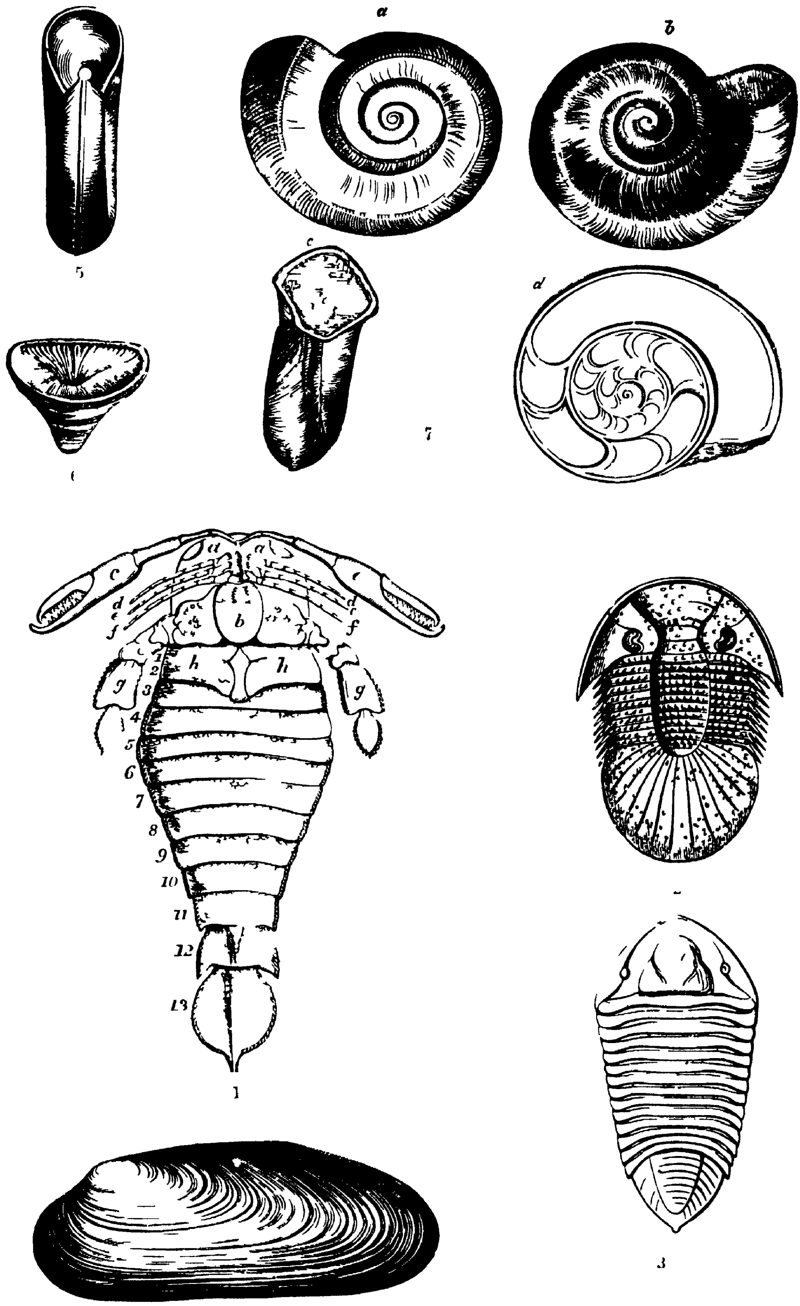


DEVONIAN FOSSILS

PLATE XXXI.

DEVONIAN AND CARBONIFEROUS FOSSILS.

1. *Pterygotus anglicus* (Ag.). Lower Old Red Sandstone. Scotland. Ventral aspect. After Dr Woodward, F.R.S.
   - (*a*) *The oval Carapace.* Showing sessile eyes at the anterior angles.
   - (*b*) *The Metastoma.* (Post oval plate.)
   - (*c.c.*) *Antennules.* (Chelate appendages.)
   - (*d*) *Antennæ*, or first pair of simple palpi.
   - (*e*) *Mandibles.* Second pair of simple palpi.
   - (*f*) *First Maxillæ.* Third pair of simple palpi.
   - (*g*) *Swimming feet* The serrated edges of the basal joints serve as *maxillæ*.
   - (*h*) *Thoracic plate.* Covering the first two thoracic segments.
   - 1–6. *Thoracic segments* or Somites.
   - 7–12 *Abdominal segments* or Somites
   - 13 *Telson or Tail plate.*
2. *Bronteus flabellifer* (Beyr) Middle Devonian.
3. *Homalonotus* sp.
4. *Anodonta Jukesii* (Forb.). Upper Devonian Ireland
5. *Clymenia lævigata* (Munst.). Front view, showing siphuncle.
6. *Calceola sandalina* (Lam.). Middle Devonian.
7. *Euomphalus pentangulatus* (Sow.). Carboniferous Limestone. (*a*) Dorsal surface. (*b*) Ventral surface. (*c*) Pentagonal mouth. (*d*) Section showing chambers



DEVONIAN AND CARBONIFEROUS FOSSILS

CHAPTER XXVII.

CARBONIFEROUS SYSTEM.

THIS system contains the principal coal-deposits of the globe, and is therefore of vast economic value to mankind. The name Carboniferous came into use at a time when it was believed that no true coal existed in any other formation. It is now universally recognised as a time-name for all the clastic rocks that lie between the Devonian and Permian systems.

Distribution.—In Europe the Carboniferous System occupies large tracts in the British Isles, North France, Belgium, Germany, and Russia, where they lie conformably on the Devonian. In the Saarbrück district, Bohemia, and Russia they pass upward without a break into the Permian ; but as the result of orogenetic earth-movement, a break is found in some regions between the Lower and Upper Carboniferous.

A considerable development of this system also occurs in Southern Europe, notably on the south border of the Central Plateau of France, in the Pyrenees, and Alps. The Carboniferous rocks cross the Mediterranean basin into North Africa and appear over a wide extent of country in the Western Sahara, in the hinterland of Morocco, in Eastern Egypt, East Sudan, Arabia, and South Palestine.

From Eastern Russia the Carboniferous System extends into Siberia, China, and Japan. In the province of Shansi, in Eastern China, the productive Coal-Measures of this age have been estimated by Richthofen to occupy an area of 35,000 square miles.

Carboniferous rocks are well developed in Northern India, but their greatest development in the Northern Hemisphere is in the United States and Alaska.

In the Southern Hemisphere Carboniferous rocks occupy wide tracts in Eastern Australia, South Africa, Peru, and Bolivia. They are also present in the Antarctic continent, but their extent in that region is at present unknown.

Rocks.—There are two distinct facies of rocks represented in the Carboniferous System in both hemispheres, namely, a marine and terrestrial. The marine dominates the Lower Carboniferous, and the terrestrial the Upper Carboniferous.

The marine facies consists mainly of limestones and shales ; the terrestrial facies, of sandstones, conglomerates, grits, and shales with seams of coal and ironstone.

In Great Britain and Russia the Carboniferous rocks are comparatively undisturbed ; but in North France, Belgium, Germany, and United States they are frequently sharply folded. In almost all the great coalfields the strata, even when lying horizontal, are intersected by numerous faults, some of which are of great magnitude.

In the British Isles, Western Europe, North India, and Australia, the

Carboniferous rocks are intercalated with numerous sheets of lava and beds of tuff.

Fauna and Flora.—The fauna of the Lower Carboniferous limestones is rich in corals, crinoids, and brachiopods. Among the corals are the well-known genera *Lithostrotion*, *Cyathophyllum*, and *Syringopora*. The crinoids include many that have survived from the Devonian, and in addition we have the new genera *Actinocrinus* and *Woodocrinus*, both confined to this system.

Echinoderms are still plentiful; and brachiopods, which are numerous, are represented by *Productus*, *Spirifer*, *Athyris*, *Rhynchonella*, and *Terebratula*. The punctate *Spiriferina* is also common.

Molluscs are abundant, and the Cephalopods include *Orthoceras*, *Actinoceras*, and *Goniatites*.

Trilobites are represented by *Phillipsia* (Plate XXXIII. fig. 7) and other genera.

Sharks and other fishes are numerous and important.

Stegocephals appear in the Lower Carboniferous. They are the earliest of the amphibians. The earliest reptiles occur in the Upper Carboniferous.

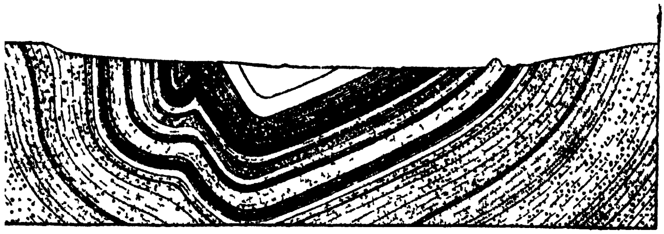


FIG. 215A.—Showing cross-section of the New Boston anthracite basin, Pennsylvania. (Penn. Geo. Survey.)

The land flora of the Upper Carboniferous is luxuriant and varied. It is specially characterised by the prevalence of gigantic Lycopods or club-mosses, ferns and fern allies, and horse-tails, all of which grew to the size of forest trees.

Of the Lycopods the principal genera are *Lepidodendron* and *Sigillaria* (Plate XXXVI. fig. 1), both of which attained a height of 100 feet. *Stigmaria*, at one time believed to be a distinct genus, is the name applied to the roots of various Lycopods.

Among the equisetums, the most important genera are *Calamites* and *Annularia*.

The fern-like forms of vegetation include *Sphenopteris* (Plate XXXVI. fig. 4), *Neuropteris* (Plate XXXVI. fig. 3), *Pecopteris* (Plate XXXVI. fig. 2), and *Alethopteris*. *Sphenophyllum dentatum* is also characteristic (Plate XXXVI. fig. 6).

The gymnosperms are represented by *Cordaites*.

The lower portion of the Upper Carboniferous is frequently marine, and, in some regions, marine beds are intercalated with the terrestrial beds. The fauna in these marine beds is mainly composed of molluscs, among which Lamellibranchs, Gasteropods, and Cephalopods are well represented, among the first being *Nucula oblonga*, *Nuculana acuta*, and *Pterinopecten papyraceus*, and among the last *Gastrioceras carbonarium* and *Goniatites Listeri* (Plate XXXIV. fig. 7).

Conditions of Deposition.—In the British Isles a downward movement set in at the close of the Devonian; but as we have already observed, the uplift of the preceding period was differential, being greatest in the north and least

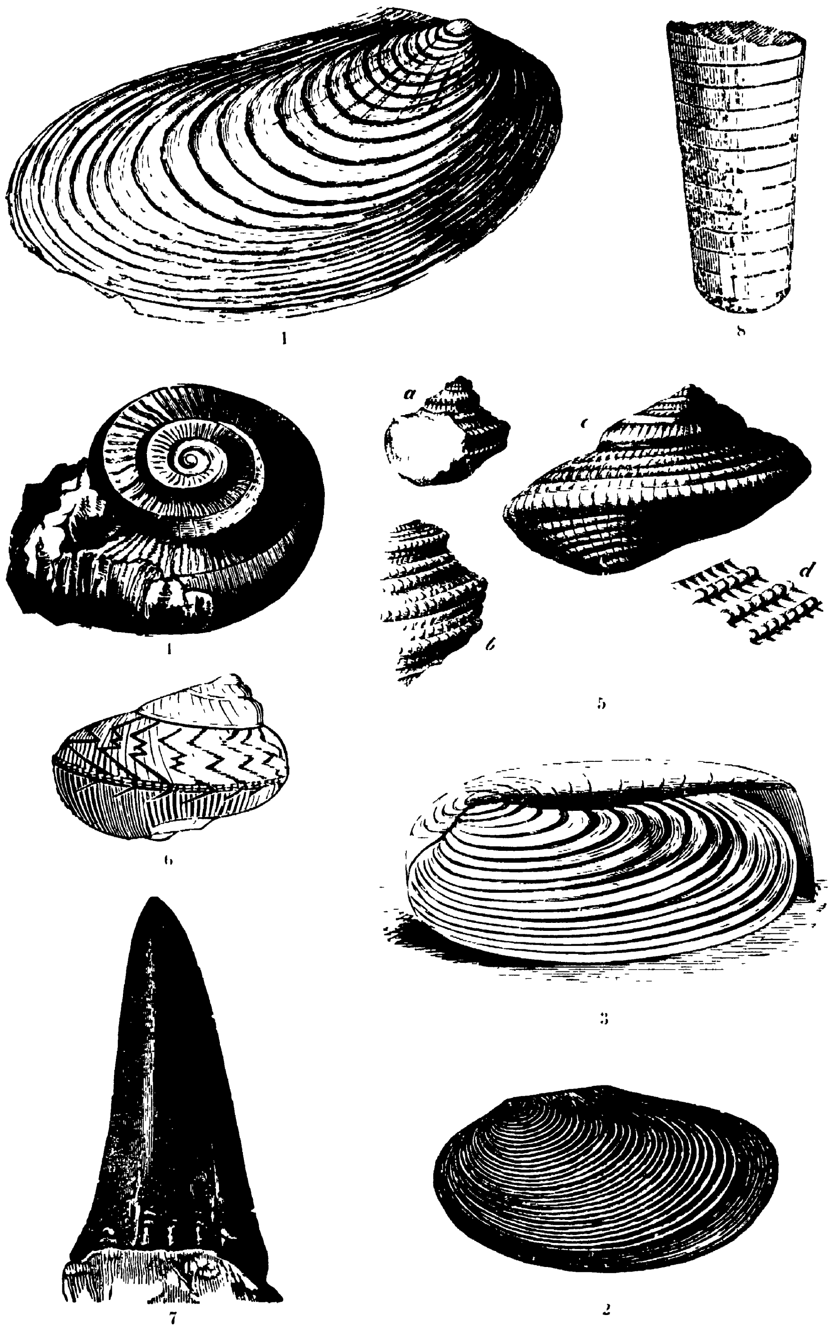
PLATE XXXII.

FOSSILS OF THE CARBONIFEROUS LIMESTONE.

1. *Posidonomya Becheri* (Bronn). Carboniferous Limestone. Venn, Trescott, etc. North Devon.
2. *Posidonomya Becheri* (Bronn). Carboniferous Limestone. Swimbridge. North Devon.
3. *Edmondia sulcata* (Phill.). Carboniferous Limestone. Yorkshire, Derbyshire, Ireland, etc.
4. *Euomphalus pentangulatus* (Sow.). Carboniferous Limestone. Yorkshire, Northumberland, etc.

5a-d. *Pleurotomaria aspera* (Sow.). Devonian Nearly allied species occur in the Carboniferous limestone.

6. *Pleurotomaria carinata* (Sow.). Carboniferous Limestone. Yorkshire, Derbyshire, Ireland, etc.
7. Tooth of *Rhizodus Hibberti* (Ag.). Lower Carboniferous. Burdie House, Leeds, etc.
8. *Orthoceras undulatum* (Sow.). Carboniferous Limestone. Derbyshire, Lancashire, etc.

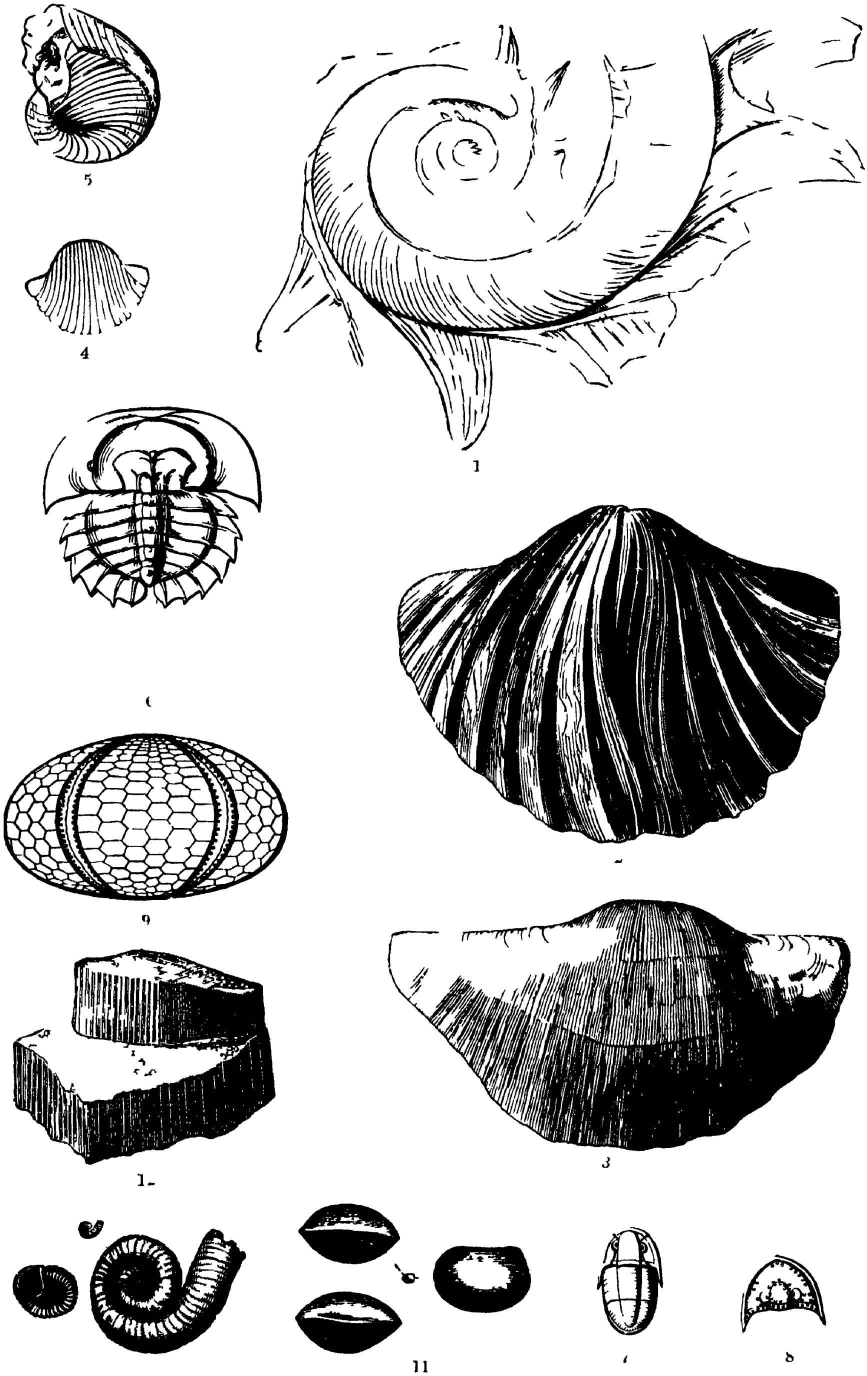


FOSSILS OF THE CARBONIFEROUS LIMESTONE.

PLATE XXXIII.

CARBONIFEROUS FOSSILS.

1. *Phanerotinus cristatus* (Sow.). Carboniferous Limestone. Derbyshire, Ireland, etc.
2. *Productus giganteus* (Mart.), var. Carboniferous Limestone—*passim.*
3. *Productus giganteus* (Mart.). Carboniferous Limestone.
4. *Bellerophon Urei* (Flemg.). Carboniferous Limestone. Rutherglen.
5. *Bellerophon hiulcus* (Sow.). Derbyshire, etc.
6. *Prestwichia anthrax.* Coal-Measures. Coalbrook Dale.
7. *Phillipsia* sp. Carboniferous Limestone.
8. *Brachymetopus ouralicus* (de Vern.) ? Derbyshire.
9. *Palaechinus gigas* (M'Coy). Carboniferous Limestone. Ireland.
10. *Spirorbis carbonarius* (Murch.). Carboniferous Limestone.
11. *Leperditia inflata* (Murch.). Carboniferous Limestone.
12. *Chætetes depressus* (Flemg.). Carboniferous Limestone. Bristol, Yorkshire, Ireland, etc.



CARBONIFEROUS FOSSILS.

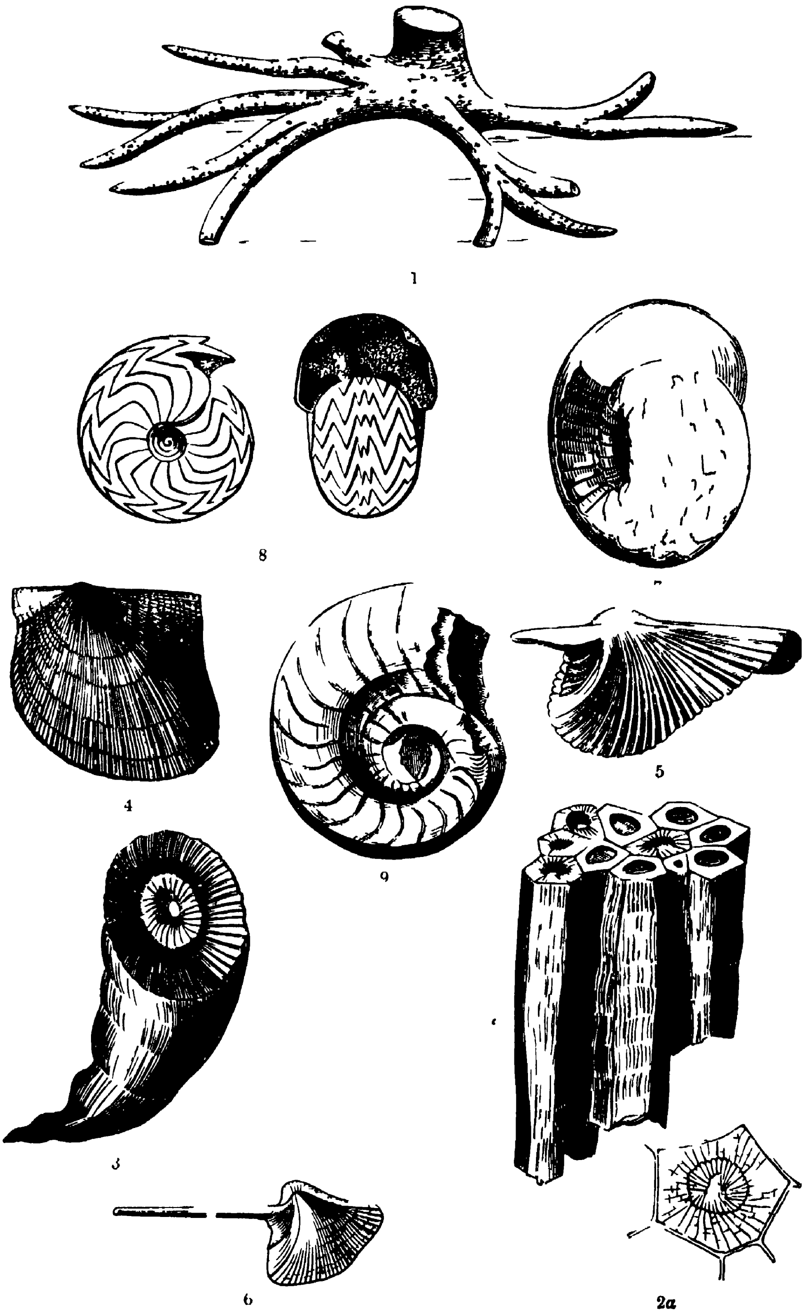
PLATE XXXIV.

CARBONIFEROUS FOSSILS.

1. *Stigmaria ficoides* (Brongn.). Root of Sigillaria. Common in every coal-field. World-wide.
2. *Lithostrotion basaltiforme* (Flem.). *L. striatum* (Flemg.). Carboniferous Limestone. Everywhere.

2*a*. Enlarged section of calice of single corallite.

3. *Clisiophyllum turbinatum* (M'Coy). Carboniferous Limestone. Scotland, Derbyshire, etc.
4. *Aviculopecten papyraceus* (Goldf.). Carboniferous (Coal-Measures). Yorkshire, Lancashire, etc.
5. *Conocardium minax* (Phill.). Carboniferous Limestone. Lancashire, Ireland, Yorkshire.
6. *Conocardium aliforme* (Sow.). Carboniferous Limestone. Lancashire, Isle of Man, Ireland.
7. *Goniatites* (*Gastrioceras*) *Listeri* (Mart.). Carboniferous Limestone. Yorkshire, Lancashire.
8. *Goniatites sphæroidalis* (M'Coy). Carboniferous Limestone. Ireland.
9. *Nautilus sulcatus* (Sow.). Carboniferous Limestone. Shropshire, Ireland, etc.

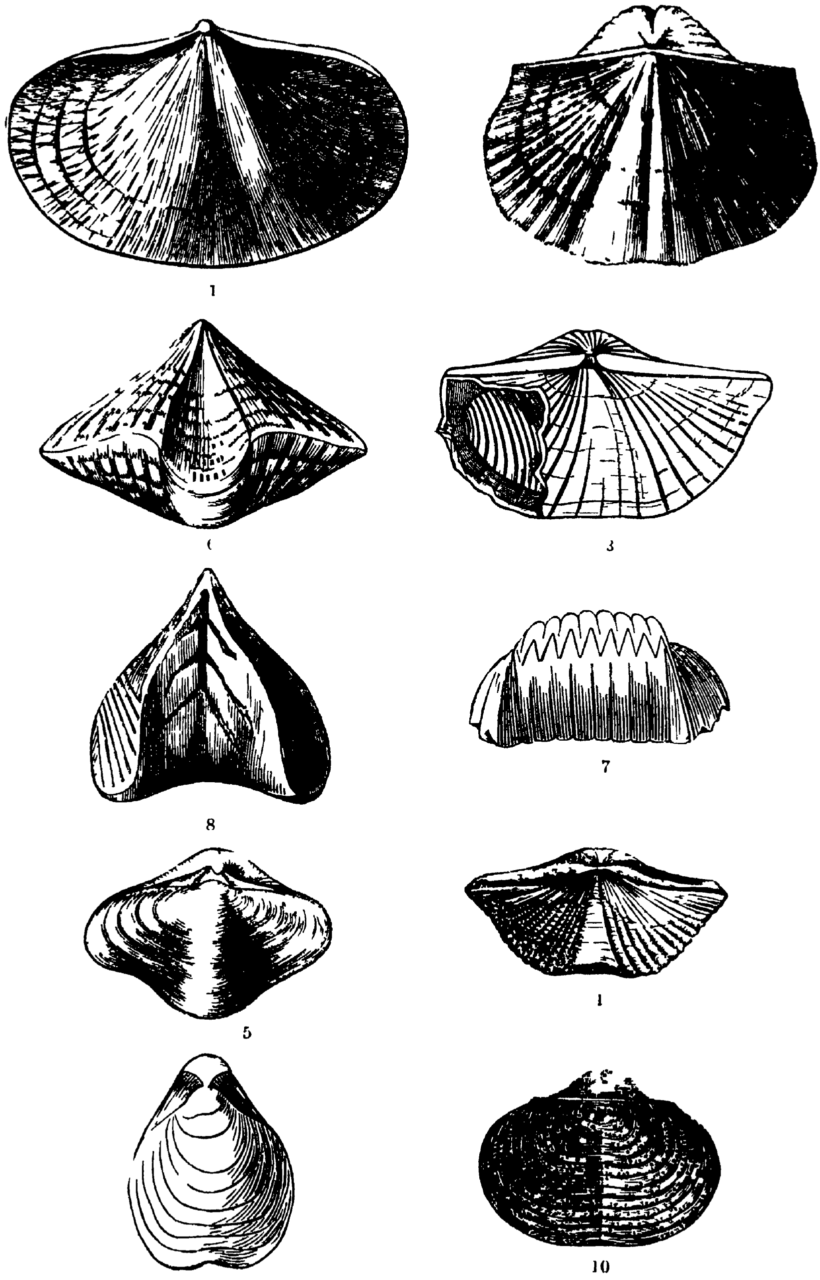


CARBONIFEROUS FOSSILS

PLATE XXXV.

FOSSILS OF THE CARBONIFEROUS LIMESTONE.

1. *Orthis resupinata* (Martin). Carboniferous Limestone. Lancashire, Derbyshire, Ireland, etc.
2. *Spirifer (rotundata) pinguis* (Sow.). Carboniferous Limestone. Lancashire, Derbyshire, Ireland, etc.
3. *Spirifer trigonalis* (Martin). Showing spiral appendages. Carboniferous Limestone. Derbyshire, Lancashire, Arran, etc.
4. *Spirifer striatus* (Martin). Carboniferous Limestone. Lancashire, Derbyshire, Ireland, etc.
5. *Spirifer glaber* (Martin). Carboniferous Limestone—*passim*.
6. *Spirifer cuspidatus* (Martin). Carboniferous Limestone. Bristol, Yorkshire, etc.
7. *Rhynchonella pleurodon* (Phill.). Carboniferous Limestone. Lancashire, Ireland, Derbyshire.
8. *Rhynchonella acuminata* (Mart.). Carboniferous Limestone Yorkshire, Derbyshire, Ireland, etc.
9. *Terebratula hastata* (Sow.). Carboniferous Limestone. Common everywhere.
10. *Productus punctatus* (Martin). Carboniferous Limestone. Yorkshire, Derbyshire, etc.

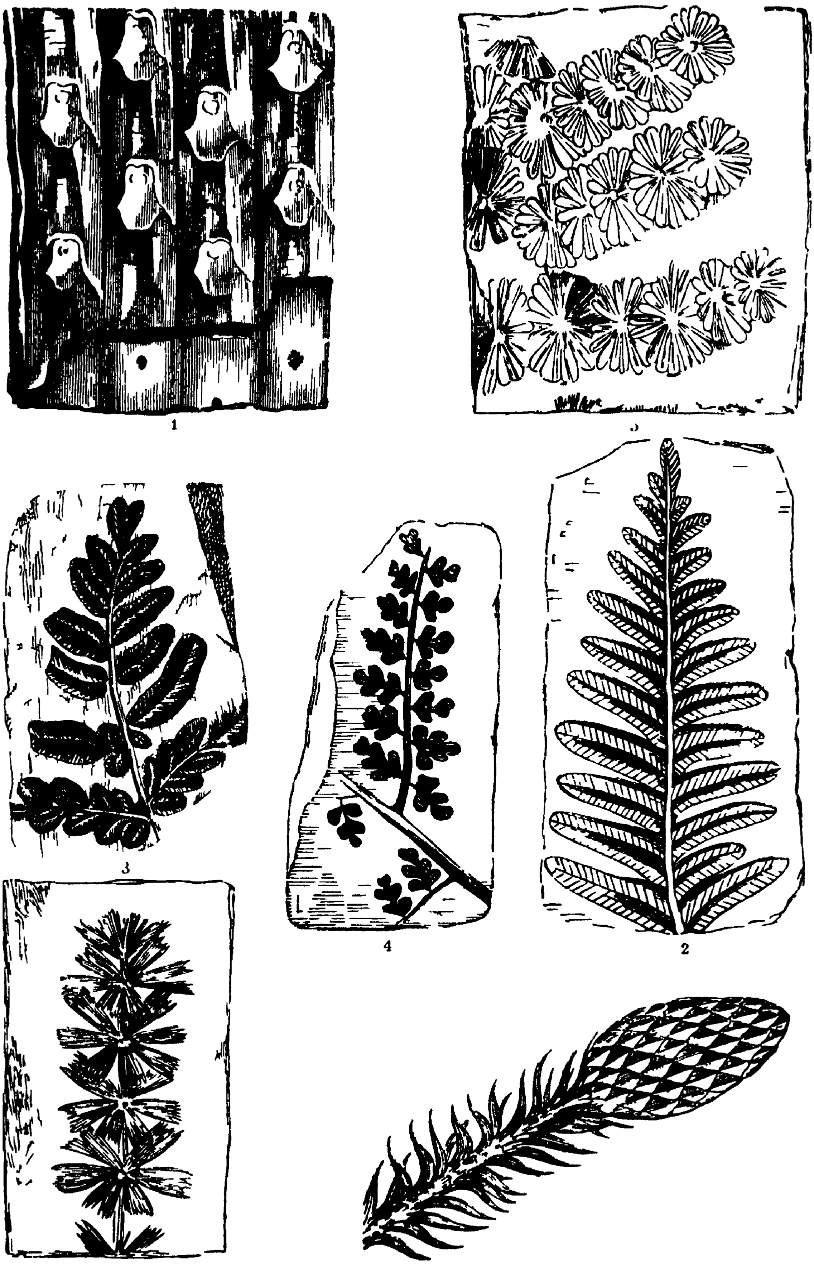


FOSSILS OF THE CARBONIFEROUS LIMESTONE

PLATE XXXVI.

FOSSILS OF THE COAL-MEASURES.

1. *Sigillaria pachyderma* (Brongn.). Coal-Measures. Northumberland, etc.
2. *Pecopteris* sp. Coal-Measures —*passim*.
3. *Neuropteris Loshii* (Brongn.). Coal-Measures. Newcastle, Yorkshire, etc.
4. *Sphenopteris Honinghausii* (Brongn.). Coal-Measures. Newcastle, etc.
5. *Annularia* (*Asterophyllites*) *brevifolia* (Brongn.). Coal-Measures.
6. *Sphenophyllum dentatum* (Brongn.). Coal-Measures. Newcastle, etc.
7. *Walchia hypnoides* (Brongn.) ? Trias.



FOSSILS OF THE CARBONIFEROUS COAL MEASURES

in the south, so that when the Carboniferous period began, the conditions of deposition in the south of England were still marine.

As the subsidence progressed, the sea once more began to advance slowly northward; but the basal calcareous deposits of the Carboniferous were laid down in the Devon region before the sea had reached the Midlands, or deposition had commenced in the north. Hence the basal beds of the Lower Carboniferous laid down in Devon are older than the basal beds further north by the time it took the sea to advance to the northern regions.

When traced northward the Lower Carboniferous beds of the south decrease in thickness and finally disappear. Thus, in the coalfields of South Staffordshire and Warwickshire, the Lower Carboniferous is either absent or but feebly represented; and where the Upper Carboniferous rests directly on the older rocks, we have a striking example of the overlap of strata due to subsidence.

While marine limestones were being deposited in the south of England, deposition was still in progress in the inland basins of the north; that is, in the Old Red Sandstone basins. Thus it happens that while the Lower Carboniferous of South England consists of marine limestones, the contemporaneous beds in Scotland are mainly red and yellow sandstones and shales with coal-seams; that is, rocks of the Old Red Sandstone facies. These beds are, in their upper division, intercalated with bands of limestone, some of which are marine and some freshwater. The lowest of the marine limestones marks the date when the advancing sea invaded the Caledonian basins; while the underlying lacustrine sandstones and shales are a record of the time it took the sea to advance to that region.

As soon as a continuous sea was established, deposition proceeded on a continuous sea-floor from south to north, the deposits being everywhere marine and contemporaneous. Hence it follows that the upper portion of the Lower Carboniferous of South England may be correlated with the Calcareous (Carboniferous Limestone) Series at the top of the Lower Carboniferous in Scotland.

The Millstone Grit, which follows the Mountain Limestone, is a littoral deposit. From this we learn that the downward movement was arrested about the close of the Upper Carboniferous, and immediately followed by a general uplift, which not only affected the British Isles, but also the whole of Northern Europe and North America.

The Millstone Grit is succeeded by the Coal-Measures of deltaic and terrestrial origin, from which we further gather that the uplift continued till there was an approach to the continental conditions of the Old Red Sandstone period. That is, the land was uplifted till large inland basins were enclosed, many of them possessing connection with the open sea in some direction.

The succession of coal-seams that exists in some of the coal basins tends to show that many minor oscillations of the land took place towards the close of the Carboniferous period.

The upper portion of the Carboniferous witnessed great crustal movements throughout Western and Central Europe, where there is a marked stratigraphical break between the Lower and the Upper Carboniferous.

Summarising the above, we find that, at the beginning of the Carboniferous period, the open sea lay to the south and the land to the north. The radiolarian cherts of Devon were doubtless laid down in deep water, the limestones of South Wales in clear water of moderate depth, and the sandstones, shales, and coals of the north in estuaries, deltas, and freshwater basins.

Each seam of coal marks an old land surface; therefore the numerous

seams that occur in some regions are an evidence of frequent oscillations of the land.

General uplift and crustal deformation began in the Carboniferous period throughout the Northern Hemisphere, producing the stratigraphical break which separates the Lower and the Upper Carboniferous in Britain and Germany. In the Southern Hemisphere the Carboniferous seems to be conformable throughout and to pass conformably upward into the Permian, from which we are led to assume that the uplift did not affect these regions, thereby permitting deposition to be continuous.

In North America, as generally throughout the Northern Hemisphere, there was pronounced uplift in the Upper Carboniferous, accompanied by continental conditions of deposition over wide tracts.

Subdivision: British Isles.—In the British Isles the Carboniferous System is divided into the following principal groups which may be described as typical of Western and Central Europe, and North America :—

	Series.	Rocks.
Upper Carboniferous	4. Coal-Measures.	Sandstones, fireclays, ironstones, and coal-seams.
	3. The Millstone Grit.	Grits, sandstones, shales.
Lower Carboniferous (Avonian)	2. The Yoredale Beds.	Shales.
	1. The Carboniferous (Mountain) Limestone.	Limestones.

It should be borne in mind that this older lithological classification is applicable only to a portion of the Pennine Region, and that the attempts to press into these local subdivisions Carboniferous strata outside that area have led to much confusion. The Yoredale phase of deposition descends to lower and lower horizons as the series is traced to the northward from the typical region; while to the southward its homotaxial equivalents are rocks whose contemporaneity is, on palæontological grounds, steadfastly denied by authorities of acknowledged competence. The Millstone Grit, another characteristic Pennine type, almost completely loses its identity in Northumberland in consequence of the occurrence there of similar rocks both higher and lower in the sequence; while, in a southerly direction, it dwindles and finally disappears in the Midlands. The rocks called Millstone Grit in the south-west region differ from the type lithologically and are not restricted to a specific horizon but appear both below and above the position assigned to it in the classification referred to.[1]

For these reasons a subdivision based on palæontological grounds is preferable. For the Lower Carboniferous the marine invertebrates serve for this purpose; while for the Upper Carboniferous the fossil plants might be advantageously used for the division of the sequence into several stages.

Generally speaking, the Lower Carboniferous is everywhere characterised by the marine facies of rocks, and the Upper Carboniferous by the deltaic and terrestrial.

In England the Carboniferous System is mainly developed in Devon, Somerset, South and North Wales, Midlands, and on both flanks of the Pennine Chain.

In Scotland the Carboniferous rocks stretch from south-west to north-east, crossing the country from sea to sea, from Ayr to the Firth of Forth, and

[1] Percy F. Kendall in "The British Isles" (*Handbuch der regionalen Geologie*, iii. 1), pp. 139–140, 1917.

occupying the great trough between the slopes of the Grampians and the Southern Uplands.

The Carboniferous of Great Britain was at one time a continuous sheet, but it now occupies a number of disconnected basins that have been produced by two systems of folds, one system, the *Pennine*, running north and south, the other, known as the *Armorican*, running from the south of Ireland to Belgium and thence to Central France. The Coal-Measures have been preserved in the troughs and removed by denudation from the crests of the folds. Obviously, the preservation of the English coals is due to the depression of the Coal-Measures in troughs that now form disconnected basins.

The Carboniferous rocks in Devon consist of shales with bands of chert, limestone, and seams of impure coal which are locally called *culm*; hence the name *Culm Measures* frequently applied to the whole series. The strata are much folded, and may be divided into two groups of beds corresponding to the Lower and Upper Carboniferous further north.

Carboniferous Limestone.—This is frequently called the Mountain Limestone. It consists of massive limestone that is 1600 feet thick in Derbyshire, and over 2000 feet thick in Ireland, where it occupies more than half of the whole island and is composed almost entirely of corals, crinoids, foraminifera, and molluscs.[1]

The Mountain Limestone is mainly composed of crinoids, but corals and foraminifera are also plentiful in it in many places. It also contains numerous brachiopods, the most common genera being *Productus*,[2] *Spirifer*,[3] *Athyris*,[4] and *Terebratula*.[5]

Gasteropods are represented by *Euomphalus* and *Pleurotomaria*; and Cephalopods by *Orthoceras*, *Nautilus*, and *Goniatites*, the last being very abundant.

Trilobites appear for the last time in the British Isles and are well represented by the genus *Phillipsia*.

When traced northward into Derbyshire, Lancashire, York, and Northumberland, the limestone becomes interbedded with thin bands of shale which increase in thickness going northward and begin to contain thin seams of coal.

In Scotland the Lower Carboniferous consists mainly of red, white, and yellow sandstones, variously coloured shales, limestones and valuable coal-seams, which are the equivalent of the Mountain Limestone of the south. These beds are divided into groups—

Lower Carboniferous	2. Calcareous or Carboniferous Limestone Series.	
	1. Calciferous Sandstone Series.	(a) Cement Stone Beds. (b) Red Sandstone Beds.

The Calciferous Sandstone Series is intercalated with vast sheets of lava and tuffs.

The calcareous division represents only the upper part of the Carboniferous Limestone of England.

In Ireland the Lower Carboniferous rocks attain their greatest development in the British Isles. They stretch as a continuous sheet from the south coast northward to Donegal Bay and Lough Foyle, and spread eastward to the Irish Sea. Altogether they occupy an area of about 15,000 square miles.

[1] E. Hall, *Physical Geography and Geology of Ireland*, 2nd ed., 1891, p. 52.
[2] Lat. *productus*=lengthened.
[3] Lat. *spira*=a coil, and *fero*=I carry.
[4] Gr. *a*=without, and *thyris*=a door.
[5] Lat. *terebratus*=pierced through or perforated.

In the south-west they resemble the Culm Series of Devon; but in the north the beds show a closer relationship to the Lower Carboniferous of Scotland. In Clare and Galway massive limestones appear with shales at the base and a few lenticular bands of chert, the total thickness of the series amounting to some 3000 feet.

Yoredale Beds.—These succeed the Mountain Limestone conformably and are typically developed in Yoredale, in Yorkshire, where they consist of flagstones, gritstones, shales, and limestones with coal-seams.

This series shows an approach to the estuarine and terrestrial conditions that prevailed in Scotland during the deposition of the Lower Carboniferous Coal-Measures of that region, with which they are perhaps contemporaneous.

The Millstone Grit.—This is a series of beds consisting of massive grits and conglomerates with subordinate bands of shale and impure limestones, some of which contain marine fossils. The grits are mostly composed of angular fragments of quartz and felspar that are probably the waste of the granitic and gneissic areas of North-West Scotland and Norway.

The rocks of the Millstone Grit are frequently current-bedded, which shows that they were deposited by water running in one direction. The presence of the shales, with sometimes marine shells, would lead to the belief that this group of beds was formed in the delta of a large river coming down from the north-east. The fossils are mostly the remains of land plants, but even these are scarce.

Coal-Measures.—These consist of a great succession of shales with subordinate beds of sandstone, impure limestone, ironstone, fireclay, and coal-seams. The original sediments were probably laid down in a great delta or estuary on the southern margin of the great Scandinavian continent.

The shales indicate quiet conditions of deposition, and the numerous seams of coal prove that luxuriant land floras grew on the swampy jungle-like mud-flats bordering the sea. The character and rank growth of the vegetation would point to the prevalence of a warm moist semi-tropical climate.

The coal is mainly composed of the spores, spore-cases, and broken remains of Lycopods, ferns, and horse-tails which accumulated to a great thickness as peat-like sheets on the steaming deltaic mud-flats.

The Lycopods which were allied to the diminutive club-mosses of the present day, grew to the size of forest trees, and their trunks, roots, foliage, and fruit are found associated with the coal. The *Calamites* or horse-tails also grew to a great size; and the ferns and fern-allies flourished in great abundance.

The coal usually rests on a seam of fireclay called *under-clay*, which was the soil in which the coal-vegetation grew, and which became fire-resisting through the exhaustion of the lime and alkalies by the growing vegetation. In these fireclays there are not infrequently found the roots and prostrate trunks of fossil trees. In some places the upright stumps have been found passing into the coal or even reaching into the *roof*, which is usually a stratum of sandstone.

The ironstone found in the Coal-Measures occurs mostly as concretionary lumps embedded in clay. Frequently the concretions are so close together as to form an almost continuous sheet. In each concretion there is usually enclosed a fossil fern-leaf or shell.

The ironstone is mostly carbonate of iron. When associated with clay it is called *clay-band ore*, and when mixed with Carbonaceous matter, *black-band ore*.

The sandstones of the Coal-Measures Series contain many fossil plants, and sometimes thin seams of coal. When highly siliceous they are called *ganister*, which is extensively used as a lining for furnaces.

The Coal-Measures Series contains the productive coal-seams of the English coalfields.

In Scotland there are three productive groups of beds in the Carboniferous System—

Upper Carboniferous { 4. Coal-Measures Series—Upper coal-beds.
3. Millstone Grit Series—Not productive.

Lower Carboniferous { 2. Carboniferous Limestone Series—Middle coal-beds.
1. Calciferous Sandstone Series—Lower coal-beds.

The bulk of the productive coal-seams of Scotland belong to the Carboniferous Limestone Series or Middle Coal-beds. Hence we find that the lower coals of Scotland are older than those of England, and, as already seen, this has arisen from the circumstance that terrestrial conditions existed in Scotland during the time that marine conditions prevailed in the South.

Productive coal-seams are not so well developed in the Carboniferous System in Ireland as in England and Scotland.

English Coalfields.—The largest and most productive coalfields in England are as follows:—

1. Bristol.—Coal-Measures 5000 feet thick, with 51 seams of coal, of which 20 are over 2 feet thick.

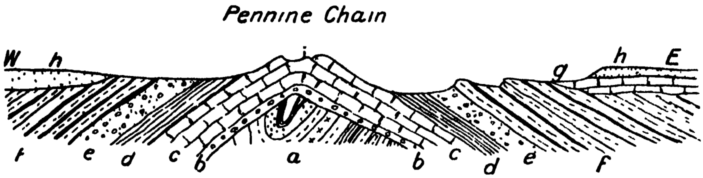


FIG. 216.—Showing section across the Pennine Chain from Lancashire to Yorkshire.

(*a*) Pre-Carboniferous rocks.
(*b*) Basement beds.
(*c*) Carboniferous (Mountain) limestone.
(*d*) Yoredale Shales Series.
(*e*) Millstone Grit Series.
(*f*) Coal-Measures Series.
(*g*) Magnesian limestone—Permian.
(*h*) Permian sandstone.

2. South Wales.—Coal-Measures from 7000 to 10,000 feet thick, with 25 seams over 2 feet thick.
3. North Wales.—Occurs in 2 coalfields—Denbighshire and Flintshire—separated by the great Bala Fault, with a displacement of 10,000 feet.
4. South Staffordshire contains the famous 10-yard Dudley seam.
5. North Staffordshire or Pottery coalfield.—The Coal-Measures are over 5000 feet thick and contain 40 seams of coal.
6. Lancashire.—Coal-Measures, 6000 feet, with 65 seams of coal.
7. Northumberland and Durham.—Coal-Measures about 3000 feet thick, with 15 seams of coal.
8. Yorkshire, Nottingham, and Derbyshire.—Lies east of the Pennine Chain. The southern extension of the Northumberland and Durham Coalfield.

Coalfields of Scotland.—The principal coalfields in Scotland are as follows:—

1. Clyde Basin.
2. Mid-Lothian or Edinburgh, and Haddington.
3. Fifeshire.
4. Ayrshire.

The Clyde Basin contains the largest and most valuable coalfield in Great Britain. It occupies the greater part of four counties and is traversed throughout its whole length by the Clyde. In Lanarkshire the coal-bearing measures are about 4000 feet thick, and contain fifteen seams of coal and six rich bands of ironstone, much of which is of the black-band variety.

Valuable cannel and oil shales occur west and south of Glasgow and also at Torbane.

Coalfields of Ireland.—The coalfields of Ireland may be divided into northern and southern groups as under :—

Northern Group	1. Leitrim. 2. Connaught and Tyrone. 3. Antrim.
Southern Group	4. Clare, Limerick, and Kerry. 5. Queen's County, Kilkenny. 6. Tipperary.

Denudation has removed the greater portion of the productive Coal-Measures in the north of Ireland.

Contemporaneous Volcanic Rocks.—The early part of the Lower Carboniferous period was disturbed by local volcanic outbursts in the south of Ireland, Devon, Isle of Man, and Derbyshire ; but it was in Scotland that the eruptions attained their greatest intensity. The eruptions began at the close of the Old Red Sandstone period, and, with intervals of rest, continued till the beginning of the Coal-Measures. In the earlier stages the outbursts, according to Sir Archibald Geikie, were characterised by the quiet outpouring of great floods of lavas of the plateau type, and in the waning phases by the emissions of piles of ashes and streams of lava from prominent volcanic vents.

The plateau-lavas covered a large area in Mid-Lothian, and in places reached a thickness of 3000 feet. They are mostly andesitic. The lavas of the volcanic type are mainly basalts.

In Derbyshire the Carboniferous Limestone is associated with sheets of basalt and olivine-dolerite, some of which are apparently contemporaneous, while others are probably intrusive sills.

Beds of volcanic tuff are interstratified with the Lower Carboniferous rocks in the Isle of Man, where intrusive sills, dykes, and agglomerates also occur.

The Carboniferous rocks in Ireland are remarkably free from contemporaneous volcanic outbursts, except at Limerick, where there are two series of volcanic rocks separated by a great thickness of sedimentary rocks. The lower series is mainly composed of andesites and basalts of the plateau type with beds of tuff, and the upper of basaltic lavas.

It is notable that the Carboniferous centres of activity are situated in the same regions as those of the Old Red Sandstone period ; and it is significant that while the rocks of the earlier period in the Midland of Scotland are calcic, those of the Carboniferous in the same region are of a distinctly alkali type.

In the North England coalfields, the Coal-Measures are intruded by many igneous dykes of probably Tertiary date. Some of these dykes, like the well-known Cockfield Dyke of Cleveland, traverse Carboniferous, Permian, Triassic, and Jurassic rocks, and displace the coal-seams like faults.

North America.—The rocks of the Carboniferous System cover an area of approximately 200,000 square miles in the United States and British North

America. They are divided into two great sub-systems, comprising eight series, as follows :—

Pennsylvanian (Littoral and lacustrine facies)	8. Monongahela Series—Upper Productive measures.	Coal-Measures.
	7. Conemaugh Series—Barren measures.	
	6. Allegheny Series—Lower Productive measures.	
	5. Pottsville Series	Millstone Grit.
Mississippian (Marine facies)	4. Kaskaskia Series.	Carboniferous Limestone.
	3. St. Louis Series.	
	2. Osage or Augusta Series.	
	1. Kinderhook Series.	

The early stages of the Mississippian in Michigan were littoral and terrestrial, but as the result of a general subsidence that affected almost the whole of the Northern Hemisphere, the deposition of the marine facies, mainly characterised by limestones, soon followed.

At the close of the Mississippian, there began a general uplift which led to a return of the terrestrial and continental conditions which characterised the Old Red Sandstone period. During this time of uplift, the Upper Carboniferous Pennsylvanian beds were laid down partly on a sea-littoral and partly in estuaries or enclosed basins. The uplift, as in Europe, continued well into the Permian.

The anthracitic and bituminous coals of Pennsylvania, Illinois, Ohio, and neighbouring States are of vast extent and great value.

India.—In Northern India, in the Spiti Valley, there is a pile of shales 4000 feet thick which is believed to represent the whole of the Carboniferous System. The lower half, known as the *Lipak Series*, is mainly composed of calcareous shales that contain a rich marine fauna, including *Productus*, many molluscs, and the trilobite *Phillipsia*.

The upper half, about 2000 feet thick, called the *Po Series*, consists of quartzites and shales, the lower portion of which contains a few fossil plants that seem to be identical with plants in the *Culm* of Europe and Australia. The upper subdivision contains many marine forms, among which bryozoans are plentiful, including the genus *Fenestella*, which has given its name to this group.

Throughout the whole length of the Himalayas and in the Chinese provinces beyond the eastern limits of India, there is a vast development of volcanic rocks which may perhaps be of Lower Carboniferous age.

The Carboniferous succession in Northern India is as follows :—

Upper Carboniferous—Po Series { (b) Fenestella Beds. / (a) Terrestrial Beds.

Lower Carboniferous—Lipak Series—Marine facies.

It will be seen from this succession that we have in India, at the close of the Lower Carboniferous, the same break as in Northern Europe and North America; which demonstrates that the uplift and crustal disturbance of the northern continents was general throughout the whole of the Northern Hemisphere. The relationship between this uplift and the volcanic activity which disturbed the Lower Carboniferous is not very clear, for it would appear that the volcanic outbursts everywhere preceded the uplift.

Australasia.—Rocks of Carboniferous age occupy extensive tracts in New South Wales, Queensland, Victoria, Western Australia, and Tasmania. In

New South Wales the Upper Carboniferous passes upward into the Permian without any evidence of a stratigraphical break. The subdivisions of the Carboniferous recognised in that State are as follows:—

Permo-Carboniferous (11,000 to 13,000 feet)	Sandstones and shales with coal-seams.
Lower Carboniferous (11,000 feet)	Sandstones and conglomerates with bands of shale and limestone.

The Lower Carboniferous rocks occur chiefly between the Hunter and Manning Rivers. The sandstones contain the gigantic club-moss, *Lepidodendron australe,* which is also found in Queensland. It would thus appear that in Eastern Australia the Carboniferous was ushered in with terrestrial conditions of deposition.

The Permo-Carboniferous is the productive coal-series of New South Wales. It is displayed over an area of 25,000 square miles in the Port Macquarie and Newcastle districts. Going southward, the Coal-Measures disappear below the Triassic Hawkesbury Sandstone, and extend along the coast to Sydney, where they have been proved at a depth of 3000 feet below sea-level.

Among the plants associated with the coals are several species of the genus *Glossopteris,* which is characteristic of the Permian of the Gondwana System of India that reached to the Mesozoic.

The marine beds of this series contain a rich Carboniferous fauna which includes the brachiopods *Athyris, Orthis,* and *Productus,* and the bryozoan *Fenestella plebeia.* The coal occurs in three horizons as determined by Professor David—

Permo-Carboniferous
6. Upper or Newcastle Coal-Measures.
5. Dempsey Series.
4. Middle or Tomago Coal-Measures, or East Maitland Series.
3. Upper Marine Series.
2. Lower or Greta Coal-Measures.
1. Lower Marine Series.

There was intense volcanic activity in the north-east portion of New South Wales, where the Carboniferous strata are intercalated with many sheets of lava, mostly rhyolite and andesite, as well as with thick beds of tuff. The Permo-Carboniferous was freer from disturbance, but the strata of this period are intercalated with beds of tuffs and contemporaneous sheets of andesite and basalt.

Associated with the Upper Coal-Measures there are massive beds of conglomerate containing scratched boulders which are believed to have been transported by ice.

In Queensland the Carboniferous rocks have been divided into five distinct series of beds as follows:—

5. Upper Bowen Series—Terrestrial beds with coal-seams and *Glossopteris.*
4. Middle Bowen Series—Partly marine and partly terrestrial, with *Productus* and *Glossopteris.*
3. Lower Bowen Series—Partly terrestrial and partly volcanic.
2. Star Series—Partly freshwater and partly marine, with *Lepidodendron.*
1. Gympie Series—Marine, with *Productus, Fenestella,* etc.

The productive Permo-Carboniferous rocks of New South Wales have

not been discovered in Victoria, but Lower Carboniferous beds are well developed in Central Gippsland, where they contain characteristic Lower Carboniferous fishes.

The Carboniferous rocks of Western Australia mainly belong to the lower or marine facies. The Permo-Carboniferous type is present in the Irwin and Collie coalfields.

In Tasmania Permo-Carboniferous rocks occupy a large tract in the south-east portion of the island. The Permo-Carboniferous is typically marine; and the upper Carboniferous, terrestrial or estuarine, consisting mainly of grits and shales with *Gangamopteris* (only in Greta series), *Glossopteris*, and *Nœggerathiopsis*. The seams of coal are thin.

Carboniferous rocks of the marine and estuarine types are present in New Zealand, and contain *Strophalosia*, *Aphanaia*, etc.

South Africa.—No Carboniferous rocks have so far been distinguished in South Africa; but it is not improbable that the upper portion of the Cape System may be the equivalent of the European Carboniferous.

Economic Products.—The supreme importance of the Carboniferous System lies in the abundance of coal that it contains. Economically this system is more important than any other, and the value of the coal annually produced from it is greater than the total value of the mineral production of all other systems put together.

The annual production of coal amounts to about 1,000,000,000 tons, valued at £500,000,000, which exceeds the value of the annual output of iron, gold, silver, tin, copper, lead, diamonds, and all other minerals more than twofold.

The ironstones produced from the Coal-Measures of Great Britain and Western Europe are still of great value.

The limestones of this system are useful as building-stone and for the production of lime for mortar and agricultural purposes.

CHAPTER XXVIII.

PERMIAN SYSTEM.

THE Permian is the youngest of the Palæozoic systems. In Southern Europe, Germany, Russia, India, Australia, and South Africa, it follows the Carboniferous quite conformably; but in the British Isles it is separated from the Carboniferous by a well-marked physical break, and in this region is more closely related to the Mesozoic than to the underlying Palæozoic formations.

In Europe the series of red sandstones, marls, conglomerates, breccias, limestones, and dolomites which follows the Carboniferous was formerly known in England as the *New Red Sandstone* to distinguish it from the *Old Red Sandstone* which underlies the Carboniferous.

The lower portion of the New Red Sandstone was subsequently found to contain fossils related to those in the Carboniferous, and the upper portion fossils related to Mesozoic forms. This led to the division of the New Red Sandstone into two distinct systems, the lower, called the Permian System, being placed in the Palæozoic; and the upper, called the Triassic System, being referred in the Mesozoic.

The name Permian was first suggested by Sir Roderick Murchison in 1841 for a great development of these rocks in the old kingdom of Perm in Eastern Russia.

The Permian System of England is the *Dyas* of German geologists.

Distribution.—The Permian System attains a considerable development in Russia, Germany, France, Alps, Sicily, Armenia, India, Australia, South Africa, and South America. The area it covers in the British Isles is comparatively insignificant.

Rocks.—In Europe the Permian consists of two distinct facies of rocks, namely, the *Dyas* type of Germany, and the *Russian* type.

In the Dyas type there are, as the name implies, two divisions or groups of beds: (1) a lower terrestrial series consisting mainly of red sandstones and conglomerates; and (2) an upper marine series of limestones and dolomites.

In the Russian type the same strata are represented, but they are interstratified in such a way as to preclude a twofold subdivision; that is, there is an alternation of terrestrial and marine beds throughout the whole system.

The prevailing rocks of the European Permian are red sandstones, in many places interbedded with bands of conglomerate, fine shales, or marls. The basal beds are frequently conglomerates, which in places pass into coarse angular breccias.

The sandstones are typically brick-red, and the so-called marls are even deeper red. In many parts of Germany the marl-slate is impregnated with a small percentage of copper-ore, and the Upper Permian there contains large masses of rock-salt and potassic salts.

The limestone, which may be regarded as characteristic of the Dyas type, is well bedded, often clayey, and usually more or less dolomitic.

In Western and Central Europe the lower portion of the Permian is intercalated with masses of contemporaneous igneous rocks.

Relationship to Carboniferous.—Throughout Western Europe the Permian rests on the denuded folds of the Carboniferous System and on older rocks. Obviously the folding and denudation took place after the deposition of the Carboniferous and before the Permian period began. In Central Europe many localities of lacustrine facies show a continuous succession from the Upper Carboniferous into the Lower Permian. In the interval that separates these two systems the greater portion of Northern Europe must have been dry land.

But in portions of North America, Eastern and Southern Europe, Central Asia, and Australia, the Carboniferous seas still existed, and on the floor of these there was laid down a continuous succession of marine sediments, covering the interval that separates the Carboniferous and Permian in Western Europe. That is, the interval representing the unconformity in Western Europe is bridged over by what may be described as *transition beds*. Therefore, in the regions where a continuous sea existed throughout the Upper Palæozoic, we get the following succession :—

$$\text{Upper Palæozoic}\begin{cases}\text{Permian.}\\ \text{Permo-Carboniferous (Transition Beds).}\\ \text{Carboniferous.}\end{cases}$$

Conditions of Deposition.—The distribution and character of the Permian in Europe afford conclusive proof that the great Scandinavian continent of North-West Europe, which played so important a rôle in the formation of the Carboniferous Coal-Measures of Western Europe, gradually increased in size till its shores encroached on Southern Europe. The late Carboniferous uplift of the northern lands, with the simultaneous retreat of the sea to the south, was merely an expression of a great crustal disturbance that affected a wide zone of country which can be traced from the southern extremity of Ireland eastward through the southern promontories of South Wales and Mendip Hills to Belgium and France and from Central France to Eastern Germany. This belt of intense folding everywhere followed an approximate W.N.W.–E.S.E. course, and raised a system of mountain folds, known as the *Armorican* Chain, which extended from the Atlantic eastward to Central Europe, but of which only the worn-down stumps now remain, mostly buried beneath the later rock-formations.

The name *Armorican* is derived from Armorica, the ancient name of Brittany, where the chain attained a great height.

The productive coal-basins of Ireland, Great Britain, North France, and Belgium lie in the northern folds of the Armorican Chain, those of Westphalia and Silesia in those of the Variscan Chain.

The general uplift we have spoken of caused the sea to retreat southward, and at the same time it established continental conditions in Northern Europe, where at different times great inland basins of the Caspian type and seas of the Mediterranean type were formed. In these Permian basins and land-locked seas, to some of which the ocean still had access, was laid down a great succession of sandy, pebbly, and clayey deposits, alternating with calcareous and dolomitic sediments and, in some regions, with salt. Some of the sandstones present the aspect of consolidated sands that may have accumulated in desert conditions not unlike those prevailing at the Isthmus of Suez, where we have a tract of more than 10,000 square miles of wind-blown desert sand, salt-water lagoon, and swamp, lying a few yards above sea-level.

In the land-locked basins the fauna was meagrely represented by forms descended from the inhabitants of the Carboniferous seas. Amphibians crawled about the marshy shores, and the land supported a vegetation closely related to the Carboniferous.

Fauna.—The conditions of life and the environment that prevailed in Northern Europe were not favourable for the development of a prolific fauna. The majority of the Carboniferous genera disappeared before the continental conditions became general, and the forms that survived were mostly small and frequently of abnormal type. Moreover, the increasing salinity of the enclosed basins was not favourable for the introduction of new genera.

The forms that were least affected by the changed conditions were the Polyzoans, which flourished in such abundance as to constitute the bulk of the limestones.

Among the Polyzoans *Fenestella retiformis* is a characteristic species.

The corals, echinoderms, and cephalopods that were so prominent in the Carboniferous seas have almost disappeared. Trilobites are unknown in the British Permian, and are but feebly represented elsewhere.

Generally the fauna of the lower division of the Permian possesses a terrestrial facies, and consists of insects (existing since Upper Carboniferous time), molluscs, crustaceans, a few fish, and amphibians, the last represented by Labyrinthodonts.

In the limestones and dolomites of the Upper Permian are found a few stunted brachiopods, lamellibranchs, gasteropods, and cephalopods.

While the fauna entrapped in the Caspian-like seas show unmistakable evidence of decadence, the genera living in the open seas continued to flourish and follow the normal processes of development. In Sicily, Armenia, and India there lived a rich and varied marine fauna, in which new genera came in to take the place of the old.

The normal marine Permian fauna is, therefore, not found in Western or Central Europe, but in Southern Europe and Asia, where it is represented by corals, bryozoans, brachiopods, and numerous molluscs.

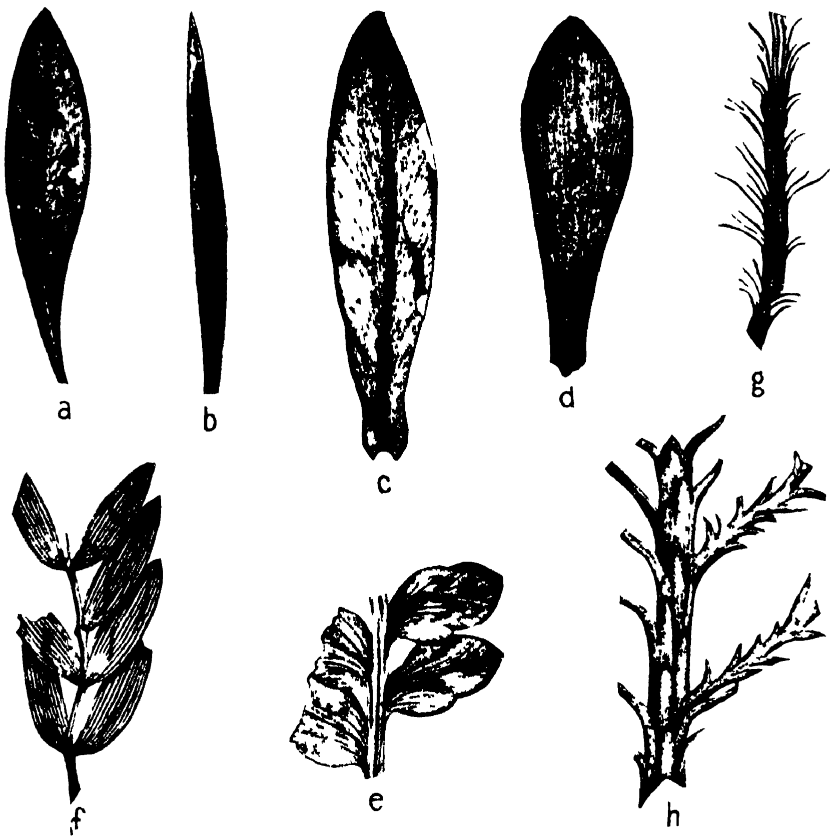
Fine Ammonites, which are so characteristic of the Mesozoic formations, began to appear for the first time in the Permian seas. The reptiles are represented in the Permian of Germany by the genera *Palæohatteria* and *Protorosaurus*; in the Permian of America by a large range of Theromorpha.

The Brachiopods include *Productus, Spirifer, Spiriferina, Terebratula*, and *Rhynchonella*; the Gasteropods, *Bellerophon, Pleurotomaria*, and *Naticopsis*; the Lamellibranchs, *Avicula, Pecten, Schizodus* (allied to *Trigonia*); and the Cephalopods, the ammonoids *Medlicottia* and *Popanoceras*, and a whole series of Orthoceratites.

Plants are represented by many survivors from the Carboniferous, and include the familiar *Calamites*, also *Walchia* (Plate XXXVIII. fig. 2) and *Callipteris*.

In America, as in Europe, the close of the Carboniferous witnessed great changes in the distribution of the land. Freshwater deposits continued to be laid down in the Coal-Measure basins in Pennsylvania, Ohio, West Virginia, and Maryland; and a vast sheet of Permian of the Mediterranean type of deposits was laid down in Texas, Kansas, and Nebraska.

The dominant feature of the Southern Hemisphere in this period is a vast pile of shales and sandstones of a deltaic and terrestrial facies, comprising what is typically known in India as the *Gondwana System*, which ranges in age from the Permo-Carboniferous to the Jurassic. This system is well developed in Australia, South America, South Africa, and Antarctic continent; and is



REPRESENTATIVE TYPES OF GLOSSOPTERIS FLORA.

(*a*) *Glossopteris communis.*
(*b*) *G. angustifolia.*
(*c*) *Gangamopteris cyclopteroides.*
(*d*) *Nœggerathiopsis hislopi.*
(*e*) *Neuropteris valida.*
(*f*) *Schizoneura gondwanensis.*
(*g*) *Phyllotheca indica.*
(*h*) *Voltzia heterophylla.*

(After Chamberlin and Salisbury.)

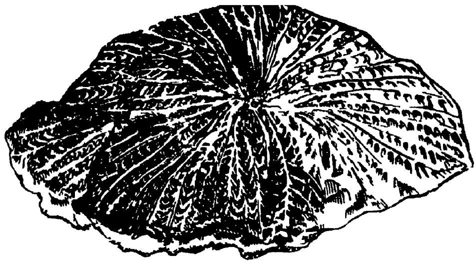
PLATE XXXVIII.

PERMIAN FOSSILS.

1. *Voltzia heterophylla* (Brongn.). Permian.
2. *Walchia Schlotheimii*. Permian.
3. *Synocladia virgulacea* (Phill.). Permian. Humbleton, Tunstall, etc.
4. *Fenestella retiformis* (Schloth.). Permian. Tynemouth, Humbleton, etc.

4*a*. Enlarged portion of *Fenestella retiformis*. Permian. Humbleton, etc.

5. *Productus horridus* (Sow.). Permian. Humbleton, Tunstall, Tynemouth, etc.
6. *Strophalosia Morrisiana* (King). Permian. Tynemouth, Humbleton, etc.



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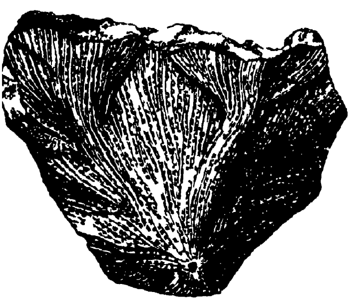

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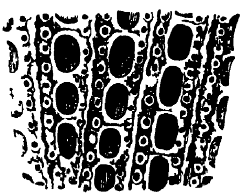

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PERMIAN FOSSILS

everywhere characterised by the presence of a peculiar terrestrial vegetation usually called the *Glossopteris* flora (Plate XXXVII.). The most distinctive types of this are the ferns *Glossopteris* and *Gangamopteris*, and the horse-tail *Schizoneura* (Plate XXXVII.).

The wide distribution of the *Glossopteris* flora in India, Australia, South Africa, and South America has given rise to the belief that the sediments, in which the remains of this flora are preserved, were laid down on the margin of a great continent which occupied the site of the existing Indian Ocean, and extended in the Australian and American quadrants to the Antarctic region. The ancient continent has been called *Gondwana Land*. It attained its greatest size and height at the close of the Carboniferous period, and existed till Mesozoic times.

The existence of an almost identical flora in regions so far apart would tend to show that the climatic conditions prevailing around the littoral of Gondwana Land were everywhere about the same. The great thickness of water-borne sediments, the Alpine glaciation, and the dense deltaic jungle vegetation whose buried remains now form valuable seams of coal, all bear evidence of an abundant rainfall and a temperate coastal climate.

Subdivision: British Isles.—A considerable development of Permian rocks occurs in England on both sides of the Pennine Chain, in the Midlands, and in Devon. In Scotland small areas of Permian strata are found in Ayrshire, Dumfriesshire, and Isle of Arran; and in Ireland a few small patches crop out in County Tyrone, and on the south shore of Belfast Lough.

The subdivision of the Permian, as it occurs on the Yorkshire side of the Pennines, is as follows:—

Upper Permian	4. Red Sandstone and Marl.
	3. Magnesian Limestone.
Lower Permian	2. Marl-slate.
	1. Yellow Sands.

The Magnesian Limestone is the most conspicuous member of the succession. In Durham it is over 600 feet thick.

On the Lancashire side of the Pennine Chain the Magnesian Limestone is subordinate in extent; and the place of the Yellow Sands is taken by sandstones, with which are associated breccias and conglomerates, the total thickness of this basal series in places being 1500 feet.

The breccias were at one time believed to be of glacial origin, but the present view is that they are ancient screes of frost-shattered rock that descended into the Permian basins.

Germany.—The Dyas type of the Permian System is well developed in the Rhine Province, Thuringia, Saxony, Bavaria, and Bohemia. It is typically displayed in the flanks of the Harz Mountains.

The two great divisions of the Dyas are—

2. Zechstein [1]—Limestones, dolomites, gypsum, rock-salt, potassic salt, and clayey beds.
1. Rotliegendes [2]—Red sandstones and pebbly beds, large sheets of porphyr and melaphyr.

These two divisions are quite distinct, and on account of overlap arising from subsidence, the *Zechstein* is found covering regions far beyond the limits of the underlying *Rotliegende*.

The copper-bearing shales at Mansfeld, on the south flank of the Harz

[1] Zechstein=*solid or tough rock*, referring to the character of the limestone.
[2] Rotliegendes=*rot*=*red*, and *liegendes*=forming the base, *i.e.* of the copper-bearing shale.

Mountains in Upper Saxony, have been famous as a source of copper for many centuries, and are worked even now. They occur at the base of the Zechstein.

Russia.—Rocks of Permian age cover an enormous tract in Eastern Russia, principally in the province of Perm, which is bounded on the east by the Ural Mountains. They follow the Carboniferous conformably, and consist of sandstones, marls, shales, conglomerates, and limestones, the latter usually dolomitic. Intercalated with these rocks there are beds of rock-salt, gypsum, and thin seams of coal.

The terrestrial beds at the base contain many land plants, including *Calamites* and *Pecopteris*, also fish and labyrinthodont remains. The limestone bands are marine, and contain several brachiopods, among which *Productus* is represented by a few species.

Marine Permian is also found in Armenia.

India.—In the Salt Range of the Punjab the Permian *Damuda* Series attains a thickness of about 10,000 feet, and contains, among other plants, the genera *Glossopteris*, *Gangamopteris*, and *Schizoneura*.

The coarse *Talchir* conglomerates at the base of the Permo-Jurassic Gondwana System contain striated and smoothed boulders which are believed to be of glacial origin.

Very remarkable are the marine Permian deposits of Timor in the Moluccas, with an extremely rich fauna in which crinoids, blastoids, brachiopods, lamellibranchs, and ammonites are numerous.

South Africa.—At the base of the Permo-Jurassic Karoo System, which occupies a prominent place in the geological structure of South Africa, there occurs a series of shales and conglomerates called the *Dwyka* Series.

The Dwyka conglomerate of this series contains striated stones and boulders that are now generally believed to be glacial.

This remarkable conglomerate occupies an extensive tract in North and South Cape Colony, Orange River State, and the Transvaal, where it forms an encircling sheet around the margin of the Karoo Basin. In the south it is about 1000 feet thick, but going northward it diminishes in thickness. It is devoid of all organic remains except at Vereeniging, where the overlying shales contain the remains of many varieties of plants, and coal-seams.

The subdivisions of the Dwyka Series are as follows:—

Dwyka Series	3. Upper Shales	600 feet.
	2. Dwyka Conglomerate	1000 ,,
	1. Lower Shales	700 ,,

North America.—The older Permian beds in the State of Kansas are marine. They are followed by sandstones containing beds of gypsum and salt, which would indicate that the Permian uplift enclosed salt-water basins in an arid region where the evaporation was greater than the precipitation.

The subdivision of the Permian in Kansas, where the development of the system may be taken as typical, is as follows:—

Permian	4. Kiger Stage	Cimarron Series.
	3. Salt Lake Stage	
	2. Summer Stage	Big Blue Series.
	1. Chase Stage	

In Texas, where the development of the Permian System is greater than in any other State, the strata attain a thickness of 7000 feet.

Permian Glaciation.—Sir Andrew Ramsay[1] was perhaps the first to notice

[1] *Geology of Great Britain*, 1878, p. 143.

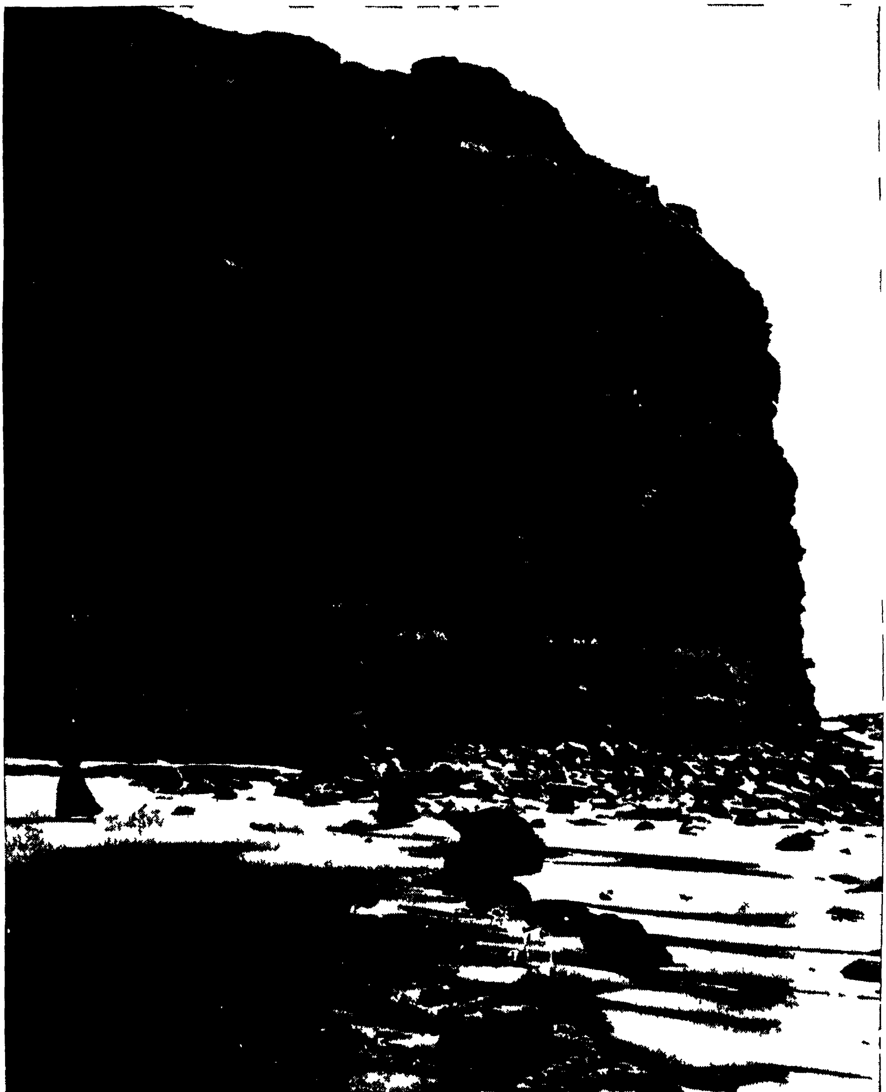


Photo by E. F. Pittman.] [*Geological Survey of New South Wales.*

DOLERITE DYKE INTERSECTING THE PERMO-CARBONIFEROUS COAL MEASURES, NOBBYS, NEWCASTLE, N.S.W.

The course of the dyke can be seen in the foreground, together with some masses of coal which have been cindered by the heat of the intrusive lava.

the similarity between certain Permian breccias and Glacial Till and more recent morainic accumulations. Since his time evidences of Permian glaciation have been recognised in several continents. Notable evidences of Permian glaciation are found in South Africa, where the famous Dwyka Conglomerate, lying near the base of the Karoo System, contains striated boulders, and possesses many of the characteristics of a consolidated glacial till; hence the name *tillite* which has been applied to it by Davis.[1] In some places it rests on a striated platform of older quartzite.

In Victoria the well-known Upper Carboniferous or Permian glacial deposits at Bacchus Marsh, Bendigo, and other places, contain smoothed and striated boulders, and rest on striated and grooved surfaces that are believed to be ice-worn.

The Bacchus Marsh glacial conglomerate is believed by some writers to occupy a position equivalent to the Talchir glacial conglomerate at the base of the Indian Gondwana System.

The Lyons Glacial Conglomerate in Western Australia has been shown by Gibb Maitland to be associated with strata containing a marine fauna which seems to fix its age as Permo-Carboniferous. It can be traced without a break in a N.N.W.–S.S.E. course from latitude 23° south to latitude 26° south.

Glacial conglomerates are associated with rocks of Permo-Carboniferous age in many parts of South America, typically in Brazil and Argentina. Near Minas, Brazil, in latitude 20° 30′ south, there is a glacial boulder-bed known as the *Orleans Conglomerate* lying below beds containing *Glossopteris* and *Gangamopteris*.

Near San Luis in Argentina a similar glacial conglomerate is associated with strata containing *Glossopteris*.

The whole of the southern portion of East Falkland Island is composed of Permo-Carboniferous strata characterised by the typical *Glossopteris* flora; and beneath these there is a clayey bed containing boulders and blocks of apparently glacial origin.

There appears to be overwhelming evidence of Permian glaciation in India, Eastern Australia, South Africa, and South America, in regions both north and south of the equator, that now enjoy tropical and semi-tropical climates. In the Old World the glaciation seems to have centred near the tropics, perhaps in Gondwana Land. In South Africa the movement of the glaciers is believed to have been southward, and in India northward, in both cases away from the equator. But in North America (eastern Massachusetts) the movement was from north to south as in the Pleistocene period and glaciation.

It is almost certain that the continental uplift which began in the Carboniferous culminated in the early stages of the Permian; and hence we are led to the belief that the glaciation of that period was not general but essentially of the Alpine type.

In India, Gondwana glacial beds occur in the Talchir district and the Salt Range, at places from 700 to 800 miles apart. In Australia, the glacial conglomerates have been traced through 20 degrees of latitude; while in South Africa the Dwyka Conglomerate has a horizontal range of 800 miles. These are significant facts, and seem to support the view that the Gondwana continent was traversed by gigantic ice-covered Alpine chains. The widespread glaciation of the regions bordering this ancient land is one of the most interesting features of the Permo-Carboniferous period in the Southern Hemisphere.

It is not improbable that the height of the mountain-chains and the amount

[1] W. M. Davis, "Observations in South Africa," *Bull. Geol. Soc. Am.*, vol xvii., 1906, p. 413.

of precipitation were sufficient to favour the accumulation of great valley-glaciers that descended to the foot-hills, where they developed as wide piedmont sheets of ice on the shores of the inland basins and land-locked seas.

Economic Products.—Rocks of Permian age produce vast quantities of rock-salt and gypsum, and also some copper.

The German Zechstein or Upper Permian is celebrated for its extensive beds of rock-salt which occur on the north of the Harz Mountains. The rock-salt at Stassfurt in Prussia is 1200 feet thick, and is followed by a zone 150 feet thick of potassium and magnesium salts. At Sperenberg, south of Berlin, the bed of salt is 3000 feet thick. But these great thicknesses are not the original ones, but are those of salt-columns piercing the over-lying strata by ascensional processes.

The beds of rock-salt and gypsum in Kansas are of great extent and value.

The copper-bearing shales at Mansfeld, in Central Germany, have been a source of copper for many centuries. At Kokand, in Turkestan, the Permian sandstones contain about one per cent. of copper in certain zones.

The world-wide occurrence of copper in rocks of Permian age is one of the unsolved riddles of this period. The suggestion has been made that the copper was extracted from the sea-water by certain marine algæ.

CHAPTER XXIX.

MESOZOIC ERA. TRIASSIC SYSTEM.

THE Mesozoic era comprises that portion of the geological record lying between the Palæozoic and Cainozoic eras, and its deposits contain a fauna and flora that form the connecting link between the ancient and existing life; hence the origin of the name, which signifies *middle life.*

The sedimentary rocks of this era are usually divided into three great systems, namely—

3. Cretaceous.
2. Jurassic.
1. Triassic.

In Northern India, South Africa, and Australia there is a continuous conformable succession of strata ranging from the Permian to the Jurassic. In England and Eastern States of North America the Trias rests unconformably on the Permian, and in other regions there are breaks in the Mesozoic succession arising from warping and differential crustal movements.

The dominant rocks of the Mesozoic formations are sandstones, shales, and conglomerates of the continental facies, with which are often associated lenticular beds of rock-salt and gypsum, and limestones and marls of the marine facies. The limestones are in part more or less dolomitic.

Generally speaking, the Mesozoic rocks are (1) more calcareous than the Palæozoic; (2) less metamorphosed; and (3) less disturbed, except where they have been entangled in the folds of mountain-chains.

As they have suffered less metamorphism, such altered rocks as slates, schists, and quartzites are relatively scarce, and seldom or never seen except in regions of intense folding and tectonic disturbance.

Mesozoic rocks take a prominent place in the geological structure of the Pyrenees, Alps, Apennines, Carpathians, Urals, Himalayas, New Zealand Alps, Andes, Rocky Mountains, and all the great mountain-chains of the globe, the age of which is therefore post-Mesozoic.

The Mesozoic formations are frequently invaded by igneous dykes and intrusive sills of Tertiary date, but except in a few isolated places of limited extent they are singularly free from intercalations of contemporaneous volcanic rocks till the close of the Cretaceous, from which it would appear that the Mesozoic era enjoyed almost complete immunity from volcanic activity throughout the whole globe.

The close of the Carboniferous period, as previously described, witnessed widespread crustal movements and uplift, which eventually led to the continental conditions of deposition so characteristic of the Permian. The continental conditions that prevailed in Western and Central Europe and other regions during the early Mesozoic were merely a continuance of the Permian conditions.

But although there is no evidence of contemporaneous folding, volcanic activity, or intense disturbance of any kind until the closing stages of the Mesozoic, the character of the sediments prove conclusively that there were minor oscillations of the land, and that in parts of the Northern Hemisphere there was a general downward movement which culminated in the Jurassic.

In the Mesozoic there was a marked decline of the brachiopods. The graptolites, trilobites, armoured fishes, *Lepidodendron*, and *Calamites* which characterise the Palæozoic era, are entirely absent. On the other hand, there is a great development in the Trias of brachiopods represented chiefly by the genus *Spiriferina* which differs from *Spirifer* in the possession of a punctate shell and a strong medial septum in the ventral valve, between the dental plates. The Jurassic and Cretaceous are characterised by the prevalence of Saurians, Ammonites, and Belemnites. But the feature which specially characterises the Mesozoic is the appearance of the earliest birds, mammals, leaved trees, and flowering plants.

Triassic System.

The Triassic is the oldest of the Mesozoic systems, and it owes its name to the three groups or series into which it is divided in Germany, where it is typically developed, and where it was first studied in detail.

Rocks and Distribution.—Throughout the globe there are two dominant facies of Triassic deposits, the *Continental* and *Marine*, each occupying a well-defined geographical province.

In Europe, where the two facies of the Trias was first recognised, the Continental facies, which is mainly developed in the great Germanic Basin of Central Europe, is called the *German*; and the Marine facies, which is typically developed in the Maritime Alps, the *Alpine*.

The *Continental* Trias consists mainly of red sandstones, shales, and conglomerates, with beds of rock-salt and gypsum.

The *Alpine* Trias is mainly composed of thick masses of marine limestone, with beds of marls and shales containing marine shells.

The fossil remains found in the rocks of the German facies are chiefly those of land plants and land animals. The sandy beds frequently exhibit current-bedding, are often ripple-marked, sun-cracked, and imprinted with the tracks of land animals. These features, when taken in conjunction with the prevailing red colour of the sediments and the intercalated beds of gypsum and rock-salt, seem to show that the rocks of this facies of the Trias originated in continental conditions, perhaps not unlike those now prevailing in the Caspian Basin, where the deposits are partly desert sands and partly fluvio-lacustrine.

The inland basins in which these continental deposits accumulated were probably situated in maritime regions where slight oscillations of the land permitted occasional invasions of the sea.

The meagre land flora, the scanty fauna and the existence of the beds of gypsum and rock-salt indicate the prevalence of arid climatic conditions in a wide zone passing through Western and Central Europe. Desert conditions also prevailed in the Eastern States and Western Interior Basin of North America.

The fluvio-lacustrine or continental Trias of South Africa, with its numerous carnivorous and herbivorous saurians and amphibians, and the complete absence of intercalated deposits of rock-salt and gypsum, clearly points to the prevalence

of luxuriant jungle conditions somewhat similar to those now prevailing in the great lake-basins at the sources of the Nile.

The *German* Trias is extensively developed in Germany, where it occupies a larger area than any other formation. It also occurs in North-East Russia, in the British Isles, in the Eastern States, and Interior Basin of North America.

The Alpine Trias, which is the time-equivalent of the Continental facies, is extensively developed in Southern Europe, Asia Minor, Northern India, Japan, South-East Asia, New Zealand, Peru, Mexico, and Western States of North America.

GERMAN OR CONTINENTAL FACIES.

Subdivisions in Germany.—There are three main divisions of the Trias recognised in Germany, namely—

3. Keuper [1]—Red sandstones, conglomerates, and shales.
2. Muschelkalk [2]—Massive, in part dolomitic, limestones.
1. Bunter [3]—Red sandstones, conglomerates and shales, with beds of gypsum and rock-salt.

The Bunter Series.—This series was deposited partly in inland seas and partly on the dry land as wind-blown sands. The sandstones are frequently current-bedded, and the tracks of land reptiles are sometimes found in both the shales and sandstones, which tends to show that they were deposited in shallow bays, estuaries, or deltas. In many cases the tracks occur in muddy sediments that are sun-cracked, which would indicate tidal conditions of deposition, or the existence of marshy swamps subject to occasional inundations. The prevailing colour of the rocks is red, which is characteristic of desert sands that have been subject to the oxidising influence of the atmosphere.

The Bunter Sandstone follows the Permian quite conformably.

Among the few fossils found in the lower part of the series are the characteristic species *Estheria minuta*, a diminutive crustacean, and *Gervillia Murchisoni*. About the middle of the series the sandstones contain the footprints of the amphibian *Chirotherium* and the remains of the Labyrinthodont, *Trematosaurus Bronni*.

In the upper part of the series the sandstones are in some regions, notably in Thuringia, intercalated with mud-beds of dolomitic limestone containing many fossils, among which is the characteristic Lamellibranch, *Myophoria costata*. Other common forms are *Myophoria vulgaris*, *Gervillia socialis*, *Pecten discites*, and *Lingula tenuissima*, all found in the overlying Muschelkalk.

The fine-grained micaceous sandstones of the Eifel contain numerous plant remains, among which occur the peculiar conifer *Voltzia* of world-wide distribution, and a species of *Equisetum*.

The Muschelkalk Series.—This attains a thickness of 1000 feet, and is mainly calcareous and marine. It follows the Bunter Sandstone quite conformably, and its presence is an evidence of subsidence followed by the trespass of the sea into the Bunter basins, which were obviously situated in maritime regions.

The lower and upper portions of the Muschelkalk consist of thin-bedded limestones and marls, and the middle portion, of dolomites with beds of gypsum and salt-bearing marls.

[1] A local name for a parti-coloured substance.
[2] *Muschel*=shell, *kalk*=limestone.
[3] *Bunt* =variegated. The full name is Buntsandstein =variegated sandstone.

The series contains many bands that are richly fossiliferous. The lower beds contain numerous fine examples of *Natica gregaria* and *Dentalium torquatum*; and these are followed by beds crowded with *Myophoria orbicularis*. Among other common forms in the Lower Muschelkalk are *Terebratula vulgaris*, *Athyris trigonella*, *Spiriferina gracilis*, *Myophoria vulgaris*, *M. elegans*, *Gervillia costata*, *Monotis Albertii*, *Lima lineata*, *Pecten discites*, and the Ammonite *Beneckeia Buchi*.

The Upper Muschelkalk is the most prolific in fossils, and among the species that occur in vast numbers are *Terebratula vulgaris*, *Myophoria vulgaris*, *Pecten discites*, *Gervillia socialis*, and *Encrinus liliiformis*. The large Nautilus *N. bidorsatus* is common, as also are the brachiopods *Spiriferina* and *Terebratula*, Ammonites are represented by the genus Ceratites, the most common species of which is *Ceratites nodosus*.

The Keuper Series.—This consists of various coloured clays, mostly red, and sandstones, which contain thick beds of gypsum and thin beds of rock-salt. Fossils occur in all the divisions of the series, but are never abundant.

The general character of the rocks and fossils show that the Keuper sediments were laid down in shallow estuaries or continental basins to which the sea had occasional access.

The estuarine conditions of the Lower Keuper are characterised by the presence of *Myophoria Goldfussi*, *M. costata*, *Lingula tenuissima*, *Estheria minuta*, and the fishes *Acrodus*, *Hybodus*, and *Ceratodus*; and the terrestrial conditions by amphibians and saurians, the latter including the genera *Mastodonsaurus* and *Nothosaurus*. Plant remains are also common.

The Middle or Main Keuper is a group of gypsum-bearing shales and marls, which passes upward into sandstones with *Equisetum arenaceum*. Still higher is the famous Stuben-Sandstone which, near Stuttgart, has yielded numerous saurian remains, including those of the crocodile-like *Belodon*, which is also found at Elgin in Scotland. At Halberstadt a quantity of Dinosaurian remains have been discovered.

The Upper Keuper, or Rhætic as it is called from its occurrence in the Rhætian Alps, contains the characteristic species *Avicula contorta*, which is limited to this stage and is therefore of zonal value. Among other forms that occur in these beds are *Modiola minuta* and *Protocardia rhætica*, but they are nowhere abundant. The coal-bearing sandstones of this stage contain the remains of many cycads, ferns, and horse-tails.

The Upper Keuper is also celebrated for its bone-bed from which, near Stuttgart, were obtained the teeth of the small marsupial-like quadruped *Microlestes antiquus*, which is the oldest known mammal. The remains of this mammal have since been found in England and United States.

Great Britain.

In England Triassic rocks are present in Devon, whence they extend into Somerset, South Wales, and the Midlands, where they spread out considerably and divide into two main arms that extend northwards, one passing on one side and the other on the other side of the Pennine Chain like the prongs of a hay-fork.

The Trias of England belongs to the *German* or Continental facies, and closely resembles the rocks and succession in Central Germany with one important exception. The Muschelkalk limestone series which so completely dominates the Middle Trias of Central Europe is entirely absent.

The Keuper follows the Bunter series in England with little or no stratigraphical break, and hence we may assume that, while the Muschelkalk was being deposited in Germany, deposits of a Continental facies continued to be deposited in England due to a continuance of the continental conditions which prevailed in the Bunter period. The German Muschelkalk may possibly be represented in England by beds that now form a part of the Keuper and Bunter in that region. If this view be correct, then we must conclude that the subsidence which permitted 1000 feet of marine beds to be deposited in Germany did not affect the British Isles.

The three main divisions of the Trias recognised in the British Isles are—

3. Rhætic—	Maximum	thickness,	150 feet.
2. Keuper—	„	„	3000 „
1. Bunter—	„	„	2000 „

The **Bunter** consists of red and variously hued sandstones and conglomerates or pebble beds of fluviatile or fluvio-lacustrine origin. The fossils comprise the remains of land plants, among which are the cypress-like conifers *Voltzia* and *Walchia*.

The **Keuper** consists mainly of marls and sandstones; but north of the Mendip Hills it has a remarkable littoral conglomerate at its base from 150 to 250 feet thick, chiefly composed of pebbles of Carboniferous limestone ranging from a few inches to three feet in diameter, set in a dolomitic limestone matrix. Hence the name *Dolomitic Conglomerate.* This conglomerate is quite local in distribution, and is obviously a shore deposit formed at the foot of a steep range rising abruptly from the edge of an enclosed sea.

All through the south-west of England the Keuper beds overlap the Bunter; and even the Lower Keuper is overlapped by the Upper Keuper, which is conclusive evidence of subsidence accompanied by a fairly rapid advance of the waters of the inland basin. Such conspicuous overlap as may be seen on the Welsh borders could only have taken place where the land fringing the basin of deposition sloped gently down to the edge of the water.

The **Rhætic** of England forms the summit of the Keuper as in Germany. It is of marine origin; although relatively thin, it is widespread and forms the closing stage of both the German and Alpine Trias throughout Western, Central, and Southern Europe. From this we learn that the general subsidence which took place in Continental Europe at the close of the Trias also affected the British Isles; and the conspicuous overlap of the different beds of the Keuper, to which we have referred above, shows that the downward movement commenced in early Triassic times. This subsidence eventually led to the introduction of marine conditions of deposition in the English area.

The Rhætic in a way comprises *passage-beds* connecting the Triassic and Jurassic systems. It is characterised in England, as also in Germany, Southern Europe, Indo-China, and Shan States, by the presence of *Avicula* (*Pteria*) *contorta*, which was first described by Portlock from examples found near Portrush, in Ireland.

Among other fossils found in the English Rhætic are *Protocardia rhætica* and *Estheria minuta*, both of world-wide distribution. At the base of the Rhætic there is a bone-bed which has yielded the teeth of a small mammal, which has been referred to the genus *Microlestes*.

A small patch of Triassic sandstone near Elgin, in Scotland, has been a prolific source of saurian remains. Among the genera found there are *Gordonia*, *Elginia*, *Hyperodapedon*, and many others.

ALPINE TRIAS.[1]

Triassic formations of the Alpine or Marine facies are widely distributed in Southern Europe, particularly in the Eastern Alps, Apennines, Sicily, Balearic Isles, Spain, Balkan Peninsula, Carpathians; and in Turkestan, Central Asia, Northern India, Burma, Tonkin, Japan, Northern Siberia, Spitzbergen, New Guinea, New Zealand, Peru, Mexico, California, Nevada, British Columbia, and Alaska.

The Alpine Trias is typically developed in the Eastern Alps, where six divisions or groups of beds have been recognised, viz.—

6. Rhætic.
5. Noric.
4. Karnic.
3. Ladinic.
2. Anisic.
1. Scythic.

The **Scythic** division or Werfen beds are the equivalent of the Bunter Sandstone, and consist of a series of red sandy micaceous shales containing beds of gypsum and rock-salt in the lower stages, and bands of impure limestone in the upper.

The series is conformable to the Permian, and where the underlying Permian rocks are of similar character, it is difficult to fix the boundary between the two. The typical fossils are *Avicula Clarai*, *Natiria costata*, and *Tirolites* (*Ceratites*) *cassianus*, with *Myophoria costata* in the upper calcareous layers.

The **Anisic** division corresponds to the German Muschelkalk. It consists mainly of limestones with clayey bands that contain an abundance of marine fossils, among which in different localities either cephalopods, brachiopods, or lamellibranchs occur. Among the brachiopods are noteworthy *Athyris trigonella*, *Spiriferina fragilis*, *Spiriferina* (*Mentzelia*) *Mentzeli*, *Rhynchonella decurtata*, and *Terebratula vulgaris*; among the cephalopods *Ceratites trinodosus*, *Ptychites*, *Gymnites*, *Pinacoceras*; and among the lamellibranchs *Gervillia socialis*, *Myophoria vulgaris*, and *Pecten discites*. Crinoids are represented by *Encrinus liliiformis* and *Dadocrinus gracilis*.

The bedded limestones are in some localities replaced by thick, grey or white dolomite, the so-called Mendola-dolomite. The typical Mendola-dolomite is formed by Diplopores.

The **Ladinic** division and all the following groups belong to the Alpine Keuper. The Ladinic is characterised by highly varying facies, and consists mainly of limestones, dolomites, and volcanic tuffs. The chief subdivision of the Ladinic are:—

3. St. Cassian beds, or zone of *Trachyceras aon*.
2. Wengen beds, or zone of *Daonella Lommeli*.
1. Buchenstein beds, or zone of *Protrachyceras Reitzi*.

The **Buchenstein** beds contain a great number of ammonites, viz. the older types, *Ceratites*, *Balatonites*, *Hungarites*, *Ptychites*; and the younger, *Protrachyceras*, *Arcestes*, and *Soannites*. *Daonella* occurs very frequently. At the close of this stage dolerites and augite-porphyries were poured out; and this volcanic activity reaches its climax in the Wengen stage. The most important elements of the fauna of the Wengen beds are *Protrachyceras*

[1] G. Arthaber, *Die Alpine Trias des Mediterran-Gebietes* (*Lethaea Geognostica. II. Das Mesozoithum*: 1. Trias), pp. 223–487.

Archelaus, Proarcestes, Monophyllites, Soannites, Arpadites, and the lamellibranch *Daonella Lommeli*. The St. Cassian beds are famous for their rich fauna, the forms of which are, however, in certain localities, stunted and small. Gastropods predominate. The fauna includes *Trachyceras aon, Cardita crenata, Cassianella decussata, Cucullæa impressa*, and *Nucula strigilata*. The rocks of the St. Cassian beds are chiefly clayey and shaly limestones.

Another facies of the Ladinic is a limestone development of the subdivisions. To this belongs the Esinokalk and the Marmolatakalk, while to a third or dolomitic facies belongs the Schlern-Dolomit and the Wetterstein-Dolomit. The Pachycardiatuffs of the Seiser Alm form the transition beds to the Karnic.

The **Karnic** division, or the Raibler beds: the Karnic is divided into two palæontological zones, the zone of *Trachyceras aonoides* and that of *Tropites subbullatus*. This sequence indicates a conspicuous regression of the Trias sea. In some localities occur plant-bearing sandstones, and in others variegated marly strata and gypsum. Besides the two leading zonal fossils this division contains *Myophoria Kefersteini, M. Whetleyæ, Halobia rugosa, Cardita Gümbeli, Gonodon Mellingi, Ostrea montis caprilis*, and *Pachycardia rugosa*.

The **Noric** division consists either of thick-bedded or massive dolomites, the so-called Hauptdolomit (chief dolomite); or of well-bedded limestones, the Dachsteinkalk. These two facies occur in separate regions or occur in the same localities, the limestones generally overlying the dolomites. Fossils are scarce. The most important are some species of the big lamellibranch *Megalodon* (usually called *Megalodon triqueter*), *Worthenia solitaria*, and *Gervillia exilis*. Near Seefeld occur bituminous shales including a rich fauna of fishes, such as *Lepidotus, Semionotus*, and *Pholidophorus*.

In the thrust-masses, which compose the Eastern Alps, the Trias shows a different development of facies. Such a facies of the Noric division is represented by the Hallstatter Kalk, a red-coloured limestone with numerous ammonites, viz. *Pinacoceras Metternichi, Cladiscites, Arcestes, Soannites, Halorites*, and *Suvavites*, besides the lamellibranch *Monotis salinaria* and the brachiopod *Halorella amphitoma*.

The **Rhætic** division is represented by the so-called Kössener beds with the leading fossil *Avicula contorta*, which also occurs in the regions occupied by the German Trias. The uppermost Dachsteinkalk belongs likewise to this stage. Generally this division consists mainly of marly limestones that form a thin but continuous sheet, which is present in Germany and England as well as in the Alpine region, thereby proving that the partial separation of the Germanic Basin and the sea of Southern Europe ceased at this stage of the Trias.

The Trias in Other Countries.

India.—The Continental and Marine facies of the Trias are well represented in Northern India, and, as in Europe, they occur in separate geographical provinces.

The Triassic division of the Permo-Jurassic Gondwana System contains a scanty flora which includes several species of *Glossopteris*, and the beautiful fern *Danacopteris Hughesi*, found also in Tonkin and China. Besides these it contains the remains of amphibians; and among the fish remains there is a form related to the *Ceratodus* of the Trias of Europe.

The Trias of the Gondwana System is obviously of continental origin, and corresponds to the German facies of Central Europe. The Indian Gondwana,

as previously described, includes three main divisions, the Lower, Middle, and Upper, which correspond with the Permian, Trias, and Jurassic. The main divisions are as follows :—

Gondwana System	Jubbulpore Series Rajmahal Series	. . .	Jurassic.
	Mahadeva Series	Maleri Stage Kamthi Stage Panchet Stage	Triassic.
	Damuda Series Talchir Series	. . .	Permian.

The Gondwana System contains the most important coal-bearing formations in India. Valuable coal-seams occur in both the Jurassic and Permian divisions, but at the present time the domestic supplies of India are mostly drawn from the Damuda Series.

The Marine or Alpine Trias of India is splendidly developed in the Salt Range of the Punjab (Lower Trias), in the Himalayas, in Baluchistan (Upper Trias), and Tibetan Plateaux in Western Tibet. The rocks are mainly limestones interbedded with marly and shaly rocks. Fossils are exceedingly abundant and usually well preserved. Among the fossils recognised in these beds are the European species *Ammonites* (*Carnites*) *floridus*, *Daonella Lommeli*, *Monotis salinaria* (Plate XXXVIIIB. fig. 1).

Australasia.—Triassic rocks are well developed in Queensland, New South Wales, and New Zealand.

The Trias of New South Wales consists of three distinct groups—

3. The Wianamatta Shales.
2. The Hawkesbury Sandstone.
1. Narrabeen Shales.

These rocks are of continental origin and hence belong to the continental facies of the Trias. They contain thin seams of coal and numerous plant remains, among which are found the characteristic genera *Tæniopteris*, *Thinnfeldia*, and *Sphenopteris*. Fish remains are not uncommon.

In New Zealand the Trias forms the lower division of the Hokonui System. It consists of a vast pile of sandstones, shales, and conglomerates of estuarine and fluviatile origin intercalated with marine beds which contain some of the characteristic species of the Alpine Trias of Southern Europe and India, notably *Halobia Litteli* and *Monotis salinaria*. The limestones which dominate the marine Trias of the Northern Hemisphere are entirely unknown, and calcareous rocks of all kinds are conspicuously absent.

A coarse conglomerate containing many large angular blocks of granite occurs at the base of the Permo-Jurassic Hokonui System of New Zealand, and is believed to be of fluvio-glacial origin.

Typical areas of Triassic rocks in New Zealand are: the neighbourhood of Richmond and Wairoa, Nelson, Mount Potts, Mount St. Mary, Hokonui Hills, Kaihiku Gorge, and Nugget Point (East coast of South Island).

Among the fossils in the marine beds are the Brachiopods *Spirigera kaihikuana*, *Sp. Wreyi*, *Spiriferina Parki*, *Sp. kaihikuana*, *Sp. nelsonensis*, *Mentzeliopsis spinosa*, *Clavigera bisulcata*, *Dielasma Zealandica*, *Rhynchonella Zealandica*; the Lamellibranchs *Myophoria nuggetensis*, *Palaeoneilo otamitensis*, *Pseudomonotis ochotica*, *Ps. Richmondiana*, *Monotis salinaria*, *Daonella indica*, *Halobia Zitteli* var. *Zealandica*, *Halobia Hochstetteri*, *Myalina* (?) *problematica*, *Myalina* (?) *mirabilis*, *Hokonuia Parki*, *H. rotundata*; and the

FIG. 1.

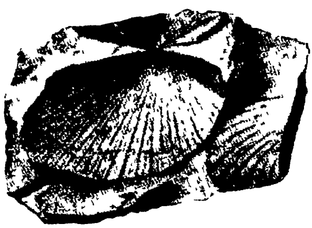


FIG. 2.

FIG. 3.

TRIASSIC FOSSILS FROM NEW ZEALAND.

FIG. 1. *Monotis salinaria* var. *Richmondiana* (Zittel).
FIGS. 2 and 3. *Halobia sp.*

Gastropoda *Pleurotomaria Hectori*, *P. hokonuiensis*, *Trochus Marshalli*, *Coronaria spectabilis*, *Conularia sp.* Cephalopods are represented by *Orthoceras sp.*, *Aulacoceras sp.*, *Grypoceras* cf. *mesodiscum*, *Proclydonautilus Mandevillei*, *Arcestes* cf. *rhæticus* W. B. Clark, *Cladiscites sp.*, *Pinacoceras sp.*, *Discophyllites* cf. *Ebneri Mojs*, *Hollandites Marianus*, and *H. Parki*. There are no corals, but several bryozoans.

The Noric and the Carnic stages of the Alpine Trias are represented. The Carnic is underlain by beds (the so-called Kaihiku Series), which, in part, seems to be somewhat older than Carnic, *i.e.* Ladinic.[1] *Pseudomonotis ochotica* is a lamellibranch, widespread in all the regions surrounding the Pacific Ocean.

The beds of conglomerate contain pebbles of granites and other igneous rocks that are unknown in the present land surface of New Zealand.

The New Zealand area in the Triassic period appears to have formed the southern coasts of a continental region that lay to the north-west in the present Tasman Sea, and was drained by large rivers that discharged their load of sand and mud in shallow deltaic seas. The prevalence of muddy sediments was probably responsible for the absence of coral-building polyps and the scarcity of Ammonites and deep-water Cephalopods.

Some of the clayey and sandy beds are crowded with broken plant remains; and in the shallow-water marine beds there are sometimes found saurian remains, among which the genus *Ichthyosaurus* has been doubtfully identified.

Among the plants recognised by Dr. Arber from the late Trias (Rhætic) rocks of New Zealand, are the genera *Chiropteris*, *Dictyophyllum*, *Thinnfeldia*, *Linguifolium*, *Cladophlebis*, *Tæniopteris*, *Sphenopteris*, *Baiera*, and *Elatophyllum*.

Linguifolium is a very characteristic fern-like plant, which occurs also in the Rhætic of Chile and of Australia, so that a connection of South America and Australia in Rhætic times seems probable.[2]

Antarctic Continent.—In Victoria Land the *Beacon Sandstone Series* covers a large tract of country. The sandstones are horizontal and intercalated with shales and seven coal-seams capped with a thick flow of dolerite, and intruded by sills of the same rock. The plant remains found in the sandstones are too fragmentary for critical determination. Hence the age of this formation may be older or younger than Trias.

South Africa.—The Karoo System of South Africa appears to be approximately the equivalent of the Gondwana System of India. It consists of a great succession of sandstones, shales, and conglomerates, with coal-seams and plant beds. All the known fossils are land or freshwater forms, and nowhere do the rocks contain evidence of marine conditions of deposition.

The lower divisions contain a *Glossopteris* flora, and the middle a flora related to that of the Middle Gondwana, as well as a remarkable assemblage of reptiles. The rock-salt and gypsum beds which characterise the continental conditions of deposition in the Northern Hemisphere are entirely absent. It would therefore appear that the Karoo deposits were laid down in great inland freshwater basins fringed with mud-flats that swarmed at certain stages with reptiles and amphibians. The climate was probably tropical or semi-tropical, but the numerous reptilians and coal-seams would seem to indicate the absence of arid desert conditions.

[1] Trechman, C. T., "The Trias of New Zealand" (*Q. J. G. S.*, vol. lxxiii. pp. 165–240, plates XVII.–XXV); and Wilckens, O., "Contributions to the Palæontology of the Trias of New Zealand" (*N.Z. Geol. Surv. Pal. Bull.*, 1924).

[2] G. Steinmann, "Rhätische Floren und Landverbindungen auf der Südhalbkugel," *Geologische Rundschau*, xi. pp. 350–357, 1921.

The Karoo System comprises four main divisions, namely—

4. Stormberg Series.
3. Beaufort ,,
2. Ecca ,,
1. Dwyka ,,

The *Dwyka Series*, as already described, is Permian and dominated by glacial conglomerates. The *Ecca Series* contains a *Glossopteris* flora related to the Permian facies of the Lower Gondwana. Among the genera of land plants common to the two systems are *Glossopteris*, *Gangamopteris*, *Nœggerathiopsis*, *Schizoneura*, *Phyllotheca*, and *Sphenopteris*, many of which are also found in the Lower and Upper Coal-Measures of New South Wales, the Bowen River Series of Queensland, the Lower Coal-Measures of Tasmania, and also in the Trias of Brazil and Argentina.

The *Beaufort Series* is mainly characterised by the occurrence in it of a number of reptilian remains, including representatives of the Anomodontia and Theriodontia, which are almost limited to this series and the Panchet Beds of the Middle Gondwana. Of the Anomodontia there is the peculiar genus *Dicynodon*; and of the Theriodontia, the genus *Galesaurus*. Among the plants in this series are *Glossopteris* and *Schizoneura*.

The *Stormberg Series* contains fish remains, including those of *Ceratodus* and some Dinosaurs, but is chiefly distinguished by a fairly abundant flora, which includes representatives of *Thinnfeldia*, *Tœniopteris*, and *Sphenopteris*, which are also found in the Upper Gondwana of India, the Triassic Hawkesbury Sandstone of New South Wales, and the Upper Coal Series of Tasmania. But correlations based on the fragmentary remains of a scanty land flora are never trustworthy or satisfactory. In a continental area if the climatic conditions remained constant, the primitive type of plant life that prevailed in the Early Mesozoic would probably show little progressive development throughout the whole of the Triassic.

North America.—The Continental and Marine facies of the Trias are typically developed in North America, the former in the Eastern States and Central Basin, and the Marine in the Pacific States.

Continental Facies.—In the Eastern States a chain of disconnected patches of the Trias extend from Nova Scotia to South Carolina, running parallel with the present coast-line and the Appalachian Chain. The largest developments are found about the Bay of Fundy, in Connecticut River Valley, and in a belt extending southward from South New York to New Jersey, Pennsylvania, Maryland, and Virginia.

Everywhere the Trias lies unconformably on the underlying formations. The rocks are mainly sandstones and shales, with which are interbedded massive bands of conglomerate and breccia.

In New Jersey, where the continental Trias is well developed, the system has been divided into three distinct groups—

$$\text{Newark System}\begin{cases}\text{3. Brunswick}\\ \text{2. Lockatong}\\ \text{1. Stockton}\end{cases}\Bigg\}\text{Triassic.}$$

The rocks of the Newark System are poor in fossils, which comprise land plants, fresh- and brackish-water fishes, and the trails of many reptiles, skeletons being very scarce. The prevailing colour of the sandstones and shales is red. The character of the sediments and their fossils clearly show

that deposition took place in large inland basins where continental conditions prevailed.

Triassic rocks of a similar character, but containing beds of rock-salt and gypsum, occupy large tracts in Texas, South Dakota, and Wyoming; and a belt of the same rocks extends along the eastern base of the Rocky Mountains from Western Canada to New Mexico.

The plant life of this period contained numerous cycads, ferns, and conifers, the latter including the genera *Palissya, Albertia,* and *Ullmania.* The gingkos were represented by *Baiera,* which also occurs in the Upper Karoo, and first appeared in the Permian of Central Germany. The Calamites are replaced by true horse-tails; but the *Glossopteris* flora, which is so characteristic of this period in India, Australia, and South Africa, is entirely absent, as it also is from Western Asia and Europe.

Land animals were represented by numerous Labyrinthodonts and the curious dinosaurs, a group of reptiles some types of which by a number of palæontologists are believed to possess bird-like affinities. The flying saurian, *Pterosauria,* appeared for the first time at the close of the period.

Marine Trias.—The greatest development of the North American marine Trias is on the Pacific watershed, in the Sierras, California, West Humboldt Range of Nevada, Oregon, British Columbia, and Alaska. In Nevada the maximum thickness of the system is 17,000 feet, the lower division, known as the *Koipeto Series,* consisting mainly of sandstones and shales, and the upper division, the *Star Series,* of sandstones, quartzites, and limestones. In the West Humboldt Range the rocks of the Star Series are sharply folded and highly metamorphosed.

The marine fauna of this system includes many European genera, among which we have the Cephalopods *Trachyceras, Ceratites, Arcestes,* and *Orthoceras*; the Lamellibranchs *Corbula, Myophoria,* and *Daonella*; and the Brachiopods *Terebratula, Rhynchonella,* and *Spiriferina.*

Surface Features.—In England, where the Triassic rocks are mostly sandstones and shales, the Triassic areas usually exhibit gentle undulating contours. In Germany the argillaceous Keuper also forms outlines of low relief; but in the South Tyrol, where the alpine Trias is strongly developed, the softer marls have been worn away, and the limestone bands stand up as high, tent-shaped, craggy ridges and bold escarpments that combine to form the picturesque beauty for which the mountains of that region are famous.

Economic Products.—In England the Triassic rocks contain valuable beds of rock-salt, which are important as a source of the British salt supplies. The principal salt-producing areas are situated in Cheshire, Worcestershire, and North Yorkshire.

The rock-salt and gypsum beds in Texas and South Dakota are extensively worked and of considerable value.

The red sandstone and massive dolomitic limestones of the Triassic System are used for building purposes in many parts of Europe, America, and Australia.

Triassic rocks usually do not contain metalliferous deposits of any moment. In Upper Silesia the Muschelkalk is rich on zinc ores, and in the Eifel the Bunter contains lead ore. Coals of Devonian, Carboniferous, and Triassic age occur in Turkestan, but so far only the Triassic coals have been worked on a commercial scale.

CHAPTER XXX.

JURASSIC SYSTEM.

THE Jurassic is the upper division of the great succession of conformable strata of which the Triassic forms the middle division and the Permian the lower. It represents the continuation of the marine conditions of deposition ushered in by the Rhætic as the result of the subsidence which set in towards the close of the Triassic period. The Rhætic acts the part of *passage* or *transition beds* connecting the two systems, and is sometimes placed at the close of the Triassic and sometimes at the base of the Jurassic.

The name Jurassic was derived from the Jura Mountains in West Switzerland, where rocks of this age are typically developed.

Rocks.—The rocks comprising the Jurassic System in the Northern Hemisphere are mainly marine marls and limestones, that are often oolitic, with subordinate beds of sandstones and shales, with which seams of coal are sometimes associated. The conditions of deposition were mainly marine, but estuarine and terrestrial conditions were introduced in some regions through slight oscillations of the land.

In the Southern Hemisphere the rocks are mainly sandstones and shales of the continental facies; but in the Cordilleran parts of South America the marine Triassic is well developed.

Different Facies of Deposits.—It should always be remembered that the lithological character of the rocks comprising a formation bears no relation whatever to the age of the formation, but is merely an expression and record of the physical geography of the region in which the deposition of the sediments took place.

Let us once more briefly summarise the physical conditions in which clastic rocks are formed.

In past geological ages, as now, there always existed deep seas fringed with shallow estuaries and deltas, open bays and land-locked harbours, seas bounded by high, rugged coasts and by wide maritime plains, Mediterranean seas and inland salt-water seas of the Dead Sea type, and great inland freshwater lakes, some situated in humid, others in arid deserts. In all the seas, estuaries, and inland lakes existing at the same time, sediments were laid down contemporaneously, the various deposits enclosing representatives of the faunas and floras that peopled the waters and clothed the neighbouring lands.

We have already seen that in the Devonian, Carboniferous, Permian, and Triassic periods there were laid down two facies of deposits—the marine and continental—each characterised by the sediments and life peculiar to the conditions of deposition. These two facies are also found in the Jurassic, and they have doubtless been formed throughout all geological time, or ever since the great continents came into existence, just as they are forming at the present time.

Coral reefs, coralline sands, and muds are now forming on the north-east coast of Australia, and vast sheets of estuarine sands and muds are accumulating in the shallow seas fringing the northern coasts; while in the centre of that ancient and worn-down continent we find great lake-basins which are now completely filled with brick-red, wind-borne sands and desert soils, or the remains of basins now marked by chains of brackish-water lagoons and swamps, frequently encrusted with layers of rock-salt.

The coral reefs, coralline sands, and muds represent the marine facies of warm seas; the tidal mud-flats of the north, the deltaic facies; and the red desert sands and clays filling the inland basins, the continental facies of an arid interior.

In later times the marine facies will be represented by massive limestones composed of corals, echinoderms, and other distinctive life of clear sea-water; and the continental facies, by red sandstones and shaly clays, current-bedded and sun-cracked, enclosing the remains of the fishes and molluscs that inhabited the lakes, also land plants and the carcases of land animals swept into the basins by the overwhelming inundations that characterise semi-arid regions. In arid regions, where the inland basins were portions of the sea isolated by uplift, the sandstones and shales may be intercalated with lenticular beds of rock-salt and gypsum, but in humid regions favourable for the growth of a jungle vegetation and the accumulation of peaty deposits, the continental beds may be associated with seams of coal.

Estuarine and deltaic sediments are mainly fluvio-marine. On the seaward side they pass into marine deposits, and on the landward into terrestrial. They will contain the remains of the crustaceans and molluscs that find a congenial habitat on tidal mudflats and sandy shell-banks, mingled with the leaves, twigs, and trunks of land plants, the carcases of land animals carried down by rivers, and the shells of marine molluscs cast up by high tides and storms. On the wide mud-flats lying above the influence of the tides, the accumulation of peaty matter may form the material for extensive seams of coal. If the land subsides, the sea will encroach on the swampy lands, whereby the peats may become covered with a protecting sheet of sands and muds, and thereby be preserved from destruction. If further subsidence takes place, the estuarine sands may become covered with marine deposits. If an uplift now takes place, the sea will once more retreat, and we may get a repetition of the first conditions, with a new growth of vegetation on the former site, but on a new soil separated from the old by the layers of sand and mud previously laid down.

Hence, when we take a general view of a world-wide formation, such as the Jurassic, we must expect to find considerable diversity in the character of the rocks and fossil remains, notwithstanding that they may be contemporaneous; and since the estuarine is merely a pathological phase of the marine, the two distinctive genetic types of deposits must always be the *marine* and *continental.*

Distribution.—The Jurassic System is extensively developed in England, France, Germany, European and Asiatic Russia, Asia Minor, India, Japan, Borneo, New Guinea, Australia, New Zealand, South Africa, Chile, Peru, Bolivia, Western States of America, and Alaska.

Although the Jurassic was not a period of mountain-building, we know that widespread land movements took place in the eastern side of the North American continent, in European and Asiatic Russia, and India.

The entire absence of Jurassic rocks in the Eastern States of North America shows that the uplift of that region lasted throughout the whole of this period,

but such uplift did not affect the western portion of the continent, where sediments continued to be laid down in the Triassic areas till the close of the Jurassic, which means that the uplift of the rocks and retreat of the sea on the east coast was balanced by subsidence of the rocks and advance of the sea on the west coast. Here the axis of the tilting movement followed a north and south direction, and passed through the great Western Interior Basin, bounded on the east by the Rocky Mountains.

In England, France, Germany, and Southern Europe, the whole of the Jurassic is present, but in the Baltic area and European Russia the lower half of the system is absent, thereby proving that the continuous subsidence in Southern Europe was compensated in the northern region by uplift during the lower half of the period, and by subsidence during the upper half. Here the axis of the tilting movement followed an approximately north-west and south-east direction.

In India, where the marine Jurassic rocks are distributed in two distinct geographical areas, each characterised by a peculiar facies, the one in the Inner Himalayas and Tibetan region, the other in the coastal region, the canting movement was the converse of that in Europe and Western Asia.

In the coastal or southern area the lower half of the system is absent, while in the Himalayan area the lower is present and the upper absent or greatly interrupted. Here we have evidence that the uplift in the south during the lower half of the Jurassic was balanced by subsidence in the north, and that the uplift in the north during the upper half of the period was balanced by subsidence in the south. The axis of this rhythmical see-saw movement was about north-west and south-east, or parallel with the tilt-axis of Europe.

This singular contrariwise tilting in Europe and India must have caused warping and enormous crustal stress in Western Asia.

Fauna and Flora.—Since the rocks of the Jurassic System, as developed in Europe, Asia Minor, Himalayan region, and Pacific States of North America, are essentially composed of marine sediments, the fossils which they contain for the most part represent the marine life of that period.

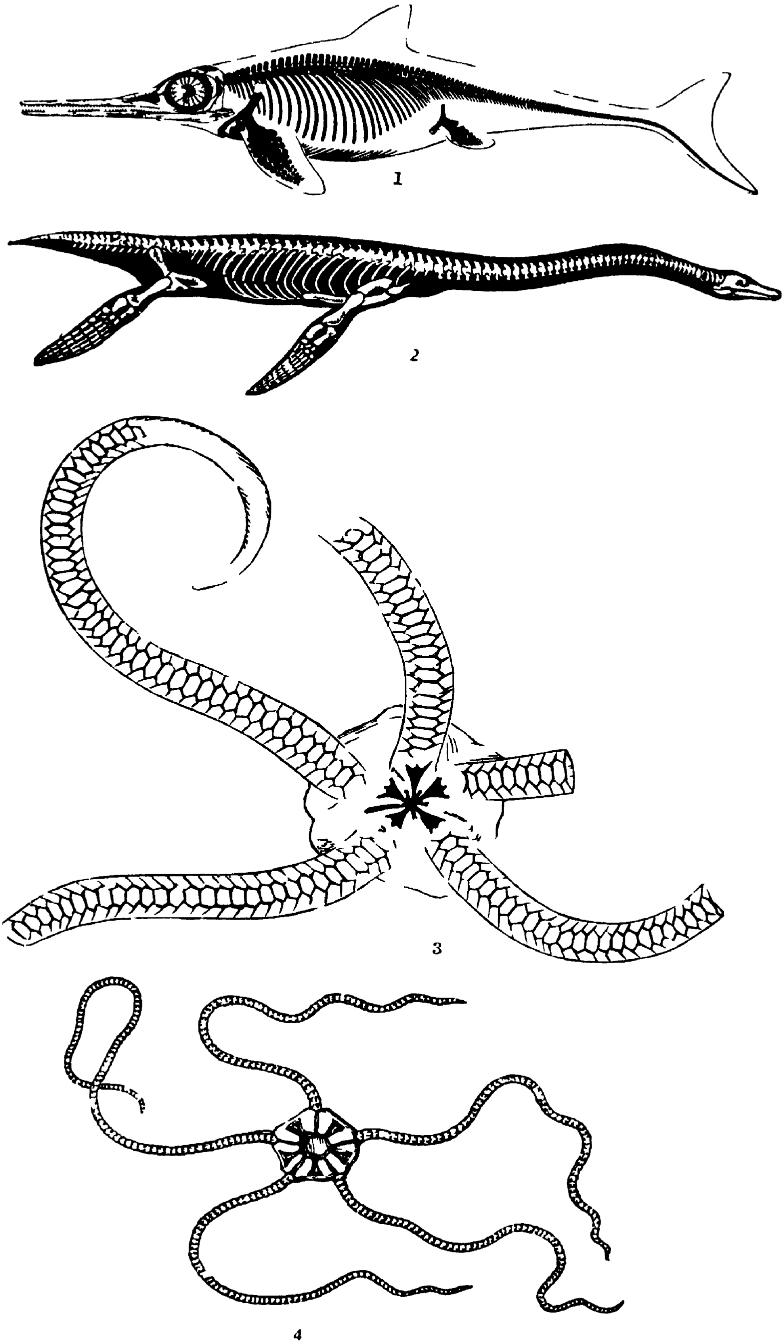
Corals are abundant in the limestones, and belong to the aporose and perforate types which have now replaced the rugose and tabulate corals of the Palæozoic era.

Sponges, foraminifera, and radiolarians are plentiful, the former in most cases well preserved.

Crinoids have become scarce, but sea-urchins, which become so prominent in the succeeding Cretaceous period, are represented by *Cidaris*, *Hemicidaris*, *Echinobrissus*, and *Pygaster*, and other echinoids.

The brachiopods are mostly of the Terebratula and the Rhynchonella type. The straight-hinged Spiriferinas are less common than in the Trias, the best known being *S. Walcotti*.

Of the molluscs, Lamellibranchs, Gasteropods, and Cephalopods are abundant. The large mussel *Inoceramus*, everywhere characterisitic of the Upper Mesozoic, makes its first appearance in the Lias (already in the Trias ?). The Jurassic is specially characterised by the great development of Ammonites, which are so numerous and important that this period has not inappropriately been called *The Age of Ammonites*. Many of the species of Ammonites are world-wide in distribution, and so limited in vertical range that they serve to divide the system into palæontological zones, each distinguished by a characteristic species. The Ammonite zones follow the same order of succession in all parts of the globe.



FOSSILS OF THE LOWER AND MIDDLE LIAS.

PLATE XXXIX.

FOSSILS OF THE LOWER AND MIDDLE LIAS.

1. *Ichthyosaurus quadriscissus* Qu. Upper Lias. Württemberg. Restoration after specimens, the skin of which is well preserved.
2. *Plesiosaurus dolichodeirus* (Conyb.). Order *Sauropterygia*, Owen (= *Plesiosauria*, Huxley). Lower Lias. Lyme Regis, Watchet.
3. *Ophioderma Milleri* (Phill.). Middle Lias. Staithes, Yorkshire.
4. *Ophioderma Egertoni* (Broderip). Middle Lias. Golden Cap, near Charmouth.

The Belemnites, a somewhat peculiar type of Cephalopods, make their first appearance in the Jurassic, and attain their maximum development before the close of the period.

Fishes are numerous, and among the genera that appear for the first time are the skates and rays. Ganoids prevail, but the bony fishes, the Teleosts, which are the dominant existing type, are represented by several species.

Reptilians which were prominent in the Middle and Upper Trias occur in such extraordinary numbers that the Jurassic is familiarly called *The Age of Reptiles*. The seas, the estuaries and deltas, the dry land and the air, swarmed with reptilians, many of them of huge size and peculiar form.

The marine types are represented by *Ichthyosaurus* [1] and *Plesiosaurus* [2] (Plate XXXIX. figs. 1 and 2); the land reptiles by the herbivorous dinosaurs,[3] some of which grew to a length of 80 feet, and a height of over 20 feet; and the flying saurians (*Pterosauria*) [4] by *Pterodactylus*, *Rhamphorhynchus*, and others.

The earliest known birds lived in the Jurassic lands. *Archæopteryx*,[5] found in the lithographic shales of Solenhofen in Bavaria, was provided with true teeth and a pair of feathers on each caudal vertebra.

The Jurassic is further distinguished by the presence of the earliest mammals, setting aside the Rhætian Microlestes, the remains of which have been found in England and Germany. These primitive mammals are believed to belong to the marsupial type, which still survives in the Australian continent.

Plant remains are found in great abundance in the terrestrial and estuarine beds, and tend to show that the Jurassic lands were clothed with a luxuriant vegetation. Cycads attain their maximum development; hence the name *Age of Cycads* sometimes applied to the Jurassic.

Ferns and conifers are also conspicuous, among the latter appearing examples of the ancestral forms of the modern pines, cypresses, and yew.

The remains of insects, including those of beetles, moths, butterflies, and flies, are abundant in the estuarine muds, having doubtless been blown seaward by strong winds. Many of the beetles belong to the tree-boring kinds, which is further evidence of the existence of forest trees on the lands fringing the Jurassic sea coasts.

Subdivisions.—For our first knowledge of the subdivisions of the Jurassic System we are indebted to William Smith, the father of English geology, who in the first decade of the nineteenth century determined the chronological succession of the Middle Mesozoic rocks of England. This work was afterwards supplemented by the investigations of Conybeare, Phillips, and others, and so important a part has the researches of English geologists played in the history of the Jurassic that many of the names used by them have passed into general use throughout the globe. And since the Ammonite zones of England have been found to be almost world-wide in distribution, the subdivisions of the Jurassic, as determined in England, may be described as typical of the system for all other regions.

The Jurassic System is very fully developed in England, France, and Germany. In other countries the succession is incomplete or not sufficiently worked out for comparative purposes.

[1] Gr. *ichthys*=a fish, and *sauros*=a reptile.
[2] Gr. *plesios*=near to, and *sauros*=a reptile.
[3] Gr. *deinos*=terrible, and *sauros*=a reptile.
[4] Gr. *pteron*=a wing, and *sauros*=a reptile.
[5] Gr. *archaios*=very old, and *pteryx*=a wing.

British Isles.

		England.		Germany.
2. *Oolite* (Upper Jurassic)	Upper	3. Purbeckian		Upper or White Jura.
		2. Portlandian		
		1. Kimmeridgian		
	Middle	2. Corallian		
		1. Oxfordian	Oxford Clay	
			Callovian	Middle or Brown Jura
	Lower	2. Bathonian (Great Oolite)		
		1. Bajocian	Fuller's Earth	
			Inferior Oolite	
1. *Lias* (Lower Jurassic)	Upper,	. . . . . .		Lower or Black Jura.
	Middle,	. . . . . .		
	Lower .	. . . . . .		

The two great divisions of the Jurassic System in England are the *Lias* or Lower Jurassic and the *Oolite* or Upper Jurassic, which correspond to the *Black Jura*, *Brown Jura*, and *White Jura* of Germany, so called after the predominating colour of the rocks of the Suabian Jurassic.

The Jurassic of England occupies a broad zone extending from the coast of Dorset to the coast of Yorkshire (fig. 216A). There are small patches in South Wales, on the border of Cheshire, and further north in Cumberland, Inner Hebrides, and east coast of Sutherland. In Ireland small outcrops occur on the borders of the Antrim plateau.

Lias.

The Lias is essentially an argillaceous formation. In England, and also in France and Germany, it consists mainly of clays and soft shales that vary in colour from grey to black. The clays are sandy in places, and in the lower part of the series in England contain bands of limestone that are sometimes shelly, but most frequently sedimentary, being composed of calcareous muds derived from the denudation of Palæozoic limestones in the neighbourhood.

In the middle or Marlstone division the clays are interbedded with bands of limestone and ironstone, the last a valuable source of iron ore in the Cleveland district of Yorkshire and in the Midland counties.

The shaly clays of the Upper Lias contain a considerable quantity of the marcasite form of pyrite. The decomposition of this ore produces sulphuric acid, which combines with the alumina of the clay and forms alum, which appears as an efflorescence on the surface of the rock.

The remains of insects are plentiful in the clays and shales. The muddy, shallow seas in which the Lias was deposited did not favour the growth of corals and bryozoans or the existence of echinoderms, all of which are rare.

The characteristic Brachiopods are *Spiriferina Walcottii* (Plate XLI. fig. 4), and *Rhynchonella tetrahedra*.

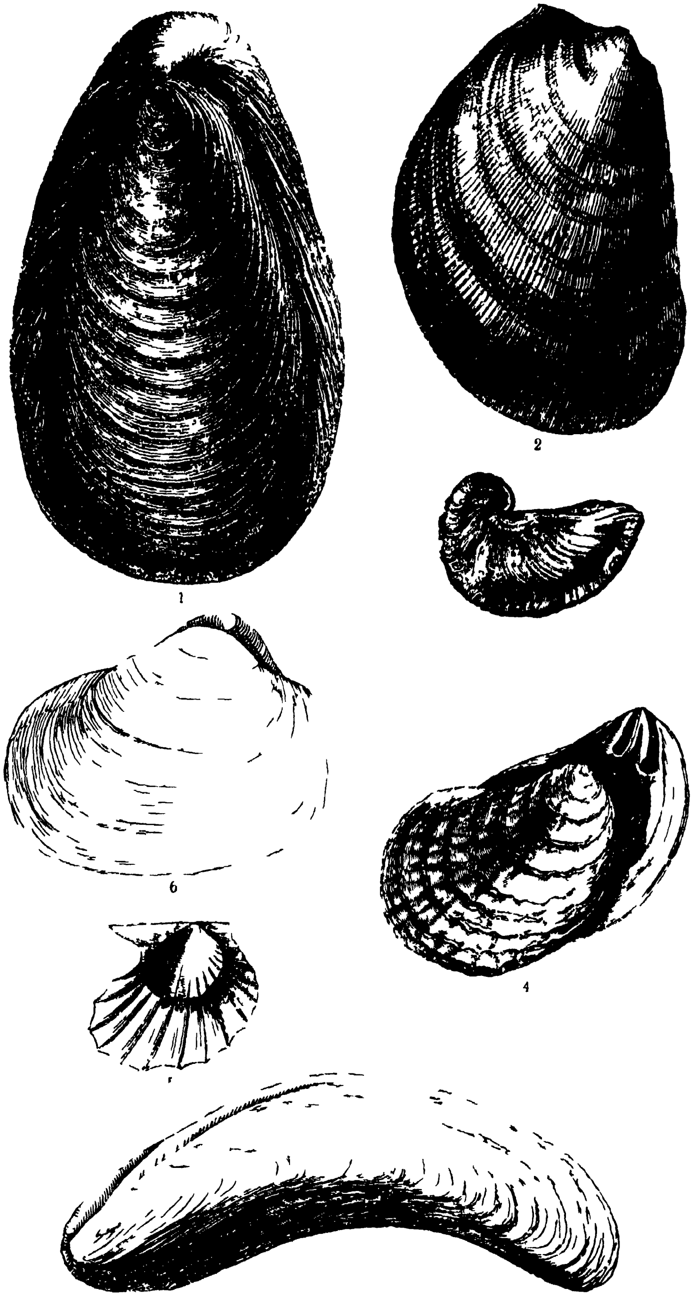
Among the abundant Lamellibranchs are *Gryphæa arcuata* (Plate XL. fig. 3), *Lima gigantea* (Plate XL. fig. 2), and *Hippopodium ponderosum* (Plate XLI. fig. 2).

Fishes are well represented, but the most important vertebrates are the reptilians, which include the marine saurians, *Ichthyosaurus* and *Plesiosaurus*, as well as flying *Rhamphorhynchidæ*.

PLATE XL

FOSSILS OF THE LOWER AND MIDDLE LIAS.

1 *Gryphæa cymbium* (Lam) Lower Lias.
2 *Lima gigantea* (Sow.) Lower Lias—*passim*
3 *Gryphæa incurva* (Sow) (=*arcuata,* Lam.) Lower Lias. Everywhere in the *Bucklandi* Zone.
4. *Plicatula spinosa* (Sow) Lower and Middle Lias—*passim.*
5. *Avicula inæquivalvis* (Sow) Lias to Kellaways Rock.
6. *Unicardium cardioides* (Phill). Lower Lias Yorkshire, Gloucestershire, etc
7. *Modiola scalprum* (Sow) Middle Lias Lyme Regis, Cheltenham.

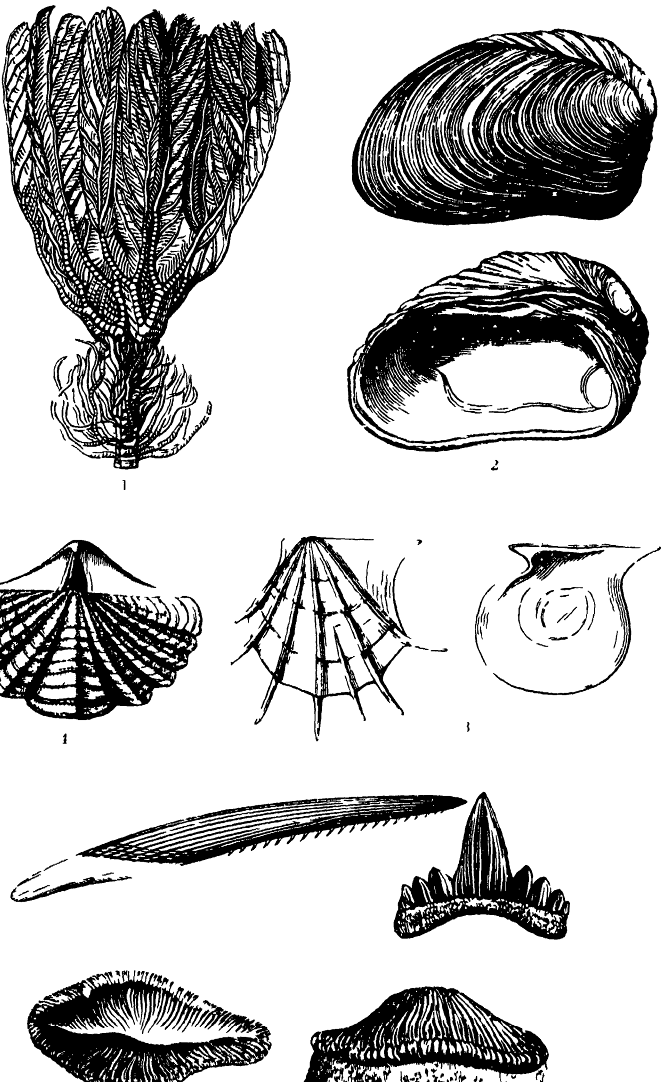


FOSSILS OF THE LOWER AND MIDDLE LIAS

PLATE XLI.

FOSSILS OF THE LOWER AND MIDDLE LIAS.

1. *Extracrinus briareus* (Mill.). Lower Lias. Lyme Regis, etc. Common.
2. *Hippopodium ponderosum* (Sow.). Lower Lias.
3. *Avicula cygnipes* (Y. & B.). Lower Lias. Bristol, Yorkshire, etc.
4. *Spiriferina Walcotti* (Sow.). Lower and Middle Lias. Lyme Regis, etc.
5. *Hybodus reticulatus* (Ag.). Fin Spine and Tooth. Lower Lias—*passim*.
6. Tooth of *Acrodus*. Lower Lias. *Bucklandi* beds.

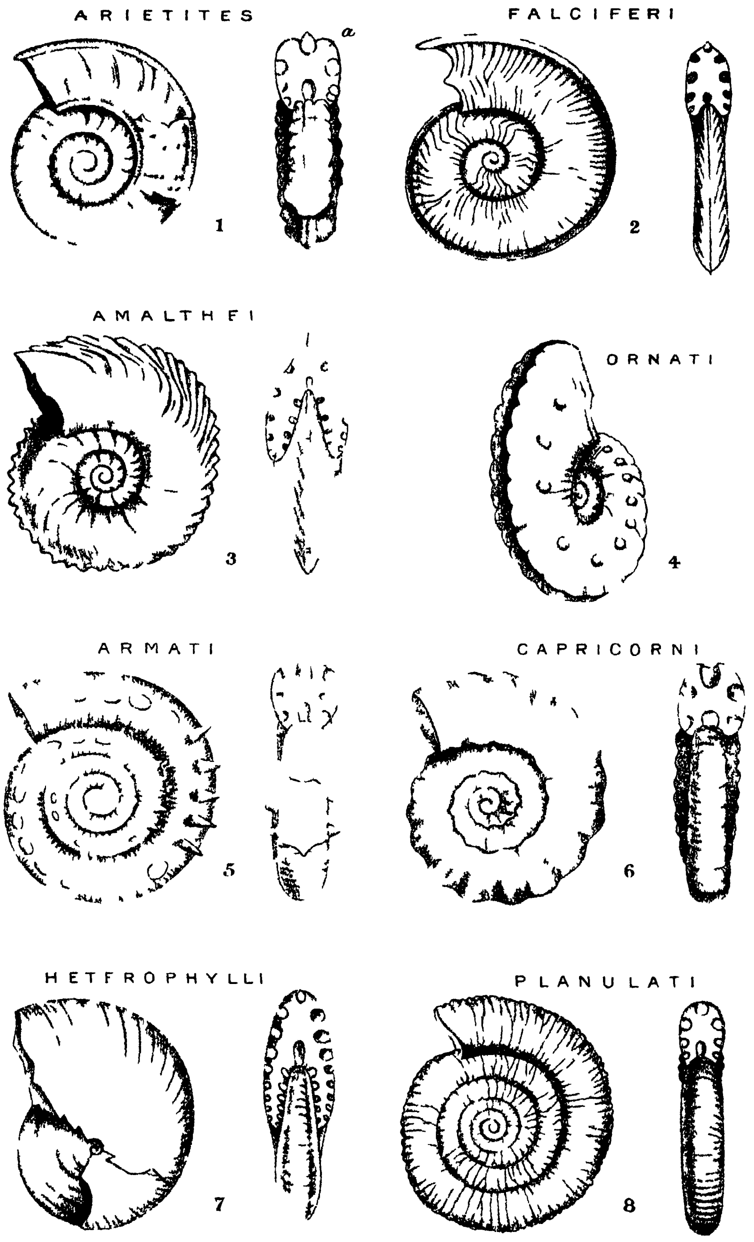


FOSSILS OF THE LOWER AND MIDDLE LIAS.

PLATE XLII.

CHARACTERISTIC JURASSIC AMMONITES.

1. *Ammonites* (*Arietites*) *obtusus* (Sow.). Lower Lias.
   Group *Arietites*. Fam. *Ægoceratidæ*.
2. *Ammonites* (*Harpoceras*) *serpentinus* (Rein.). Upper Lias.
   Group *Falciferi*. Fam. *Harpoceratidæ*.
3. *Ammonites* (*Cardioceras*) *cordatus* (Sow.). Oxford Clay and Coral Rag, etc.
   Group *Amaltheidæ*.
4. *Ammonites* (*Cosmoceras*) *Duncani* (Sow.). Oxford Clay and Kellaways Rock.
   Group *Ornati*. Fam. *Stephanoceratidæ*.
5. *Ammonites* (*Ægoceras*) *armatus* (Sow.). Lower Lias.
   Group *Ægoceratidæ*.
6. *Ammonites* (*Ægoceras*) *capricornu* (Schloth.). Middle Lias.
   Group *Capricorni*. Fam. *Ægoceratidæ*.
7. *Ammonites* (*Phylloceras*) *heterophyllus* (Sow.). Upper Lias. Chiefly Whitby.
   Group *Heterophylli*. Fam. *Phylloceratidæ*.
8. *Ammonites* (*Coeloceras*) *annulatus* (Sow.). Upper Lias—*passim*.
   Group *Planulati*. Fam. *Stephanoceratidæ*.



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CHARACTERISTIC JURASSIC AMMONITES.

Ammonites are numerous and have been used to divide the layers into zones, each characterised by a particular species, as shown below—

Upper Lias	Zone of *Ammonites jurensis*.
	,, ,, *communis*.
	,, ,, *serpentinus* (Plate XLII. fig. 2).
Middle Lias	,, ,, *spinatus*.
	,, ,, *margaritatus*.
Lower Lias	,, ,, *capricornu* (Plate XLII. fig. 6).
	,, ,, *jamesoni*.
	,, ,, *oxynotus*.
	,, ,, *bucklandi*.
	,, ,, *planorbis*.

In recent times further investigations have permitted the division of the Lias into a still much greater number of zones.

Lower Oolite.

The various divisions of the Lower Oolite are local in distribution and variable in thickness. Most of them are well developed in Dorset and South-West District, but they thin out rapidly going toward the north-east, and many of them disappear entirely before the borders of Oxfordshire are reached. Only one bed, the *Cornbrash*, the closing member of the Lower Oolite, is persistent from the south-west coast to the coast of Yorkshire.

The name *Oolite* applied to the limestones of the Upper Jurassic in England is derived from the peculiar roe-like grains of calcite of which the limestones are composed.

The characteristic limestone bands of the south are replaced, going northward, by marine sandy beds, which in Yorkshire become typically estuarine, and are locally called the *Estuarine Series*, which is the equivalent of the Inferior Oolite.

On account of the change in the character of the sediments and fossils, the Ammonite zones of the south cannot be traced into the north.

Bajocian.—This stage name is derived from Bayeux, in the Norman Department of Calvados in France, where the Lower Oolite is well developed. In England it is divided into two sub-stages—

2. Fuller's Earth.
1. Inferior Oolite.

Inferior Oolite.—This follows the Lias conformably, and extends from Dorset north-east to Yorkshire. In the South-West District it consists mainly of shelly marine limestones interbedded with clays and sandstones, but going northward the deposits in Lincolnshire contain an estuarine facies in which freshwater genera, such as *Unio* and *Cyrena,* replace the Ammonites so common in the south. Still further north, in Yorkshire, the strata consists mainly of estuarine sandstones and shales, with bands of ironstone and coal together with several calcareous beds of marine origin. These estuarine beds comprise the well-known *Estuarine Series* of Yorkshire.

The marine beds of the south-west district, which attain a thickness of 264 feet at Cheltenham, contain an abundant fauna, which includes several genera of corals, the crinoid *Pentacrinus*, and a few starfish, including *Goniaster* and *Stellaster*, as well as the sea-urchin *Cidaris*, distinguished by its club-like spines.

Of Brachiopods, *Terebratula* and *Rhynchonella* (Plate XLIV.) are fairly abundant; and among the Lamellibranchs, *Lima, Ostrea, Pecten, Pinna, Astarte* (Plates XLIV. and XLVII.), *Cucullæa, Mytilus, Pholadomya,* and *Trigonia* are common. Gasteropods are numerous, especially the genera *Pleurotomaria* and *Turbo.* The Cephalopods include many genera of Ammonites, Nautili, and the peculiar dart-shaped Belemnites.[1]

The palæontological zones of the marine facies of the Inferior Oolite are in descending order—

4. Zone of *Ammonites Parkinsoni.*
3. ,, ,, *Humphriesianus.*
2. ,, ,, *Murchisonæ.*
1. ,, ,, *opalinus.*

Recent research has permitted the subdivision of the sequence into a by far greater number of Ammonite-zones.

The estuarine facies of the Inferior Oolite in Yorkshire contains an abundant fossil flora which comprises many ferns, cycads, and conifers.

The ferns include *Pecopteris, Sphenopteris,* and *Tæniopteris* (Plate XLV.).

The cycads include *Zamites, Otozamites,* and *Cycadites.*

The conifers include *Walchia, Araucarites,* and *Taxites.*

The three calcareous beds intercalated in the estuarine series are the *Dogger* at the base, with valuable bands of concretionary iron-stone; the so-called *Millepore Limestone,* so named from the abundance of *Millepora straminea*; and the *Scarborough Limestone.*

Fuller's Earth.—This bed extends from Dorset to Bath and Cheltenham, but it is absent in the north-east counties. Its thickness nowhere exceeds 150 feet. It contains numerous fossils, which include many examples of *Ostrea, Rhynchonella, Magellania,* and *Ammonites.* The clays of this sub-stage are commercially useful for the fulling of cloth; hence the origin of the name.

Bathonian (Great Oolite).—This consists of a series of thin-bedded limestones and clays, which have been divided into three well-marked sub-stages—

Bathonian { (c) Cornbrash.
(b) Forest Marble.
(a) Great Oolite.

At the base of the Great Oolite there is what is known as the *Stonesfield Slate,* which is of peculiar geological interest. It is developed in parts of Gloucestershire and Oxfordshire, a fissile, sandy, thin-bedded limestone, and it contains a remarkable mixture of marine and estuarine forms mingled with the remains of land plants and animals. Among the most prevalent fossils are the following genera:—

Brachiopods	include	*Terebratula* and *Rhynchonella* (Plate XLIV.).
Lamellibranchs	,,	*Gervillia, Ostrea, Lima, Pecten, Astarte, Modiola,* and *Trigonia.*
Gasteropods	,,	*Natica, Patella, Nerinea,* and *Trochus.*
Cephalopods	,,	*Ammonites (Perisphinctes) gracilis, Belemnites aripistillum* and *B. bessinus.*
Fishes	,,	*Ceratodus, Hybodus,* and *Ganodus.*
Reptiles	,,	*Plesiosaurus, Cetiosaurus, Teleosaurus,* and *Megalosaurus.*
Mammalia	,,	the marsupials *Amphilestes* and *Phascolotherium.*
Plants	,,	*Pecopteris, Tæniopteris,* and *Sphenopteris.*

[1] Gr. *belemnon*=a dart.

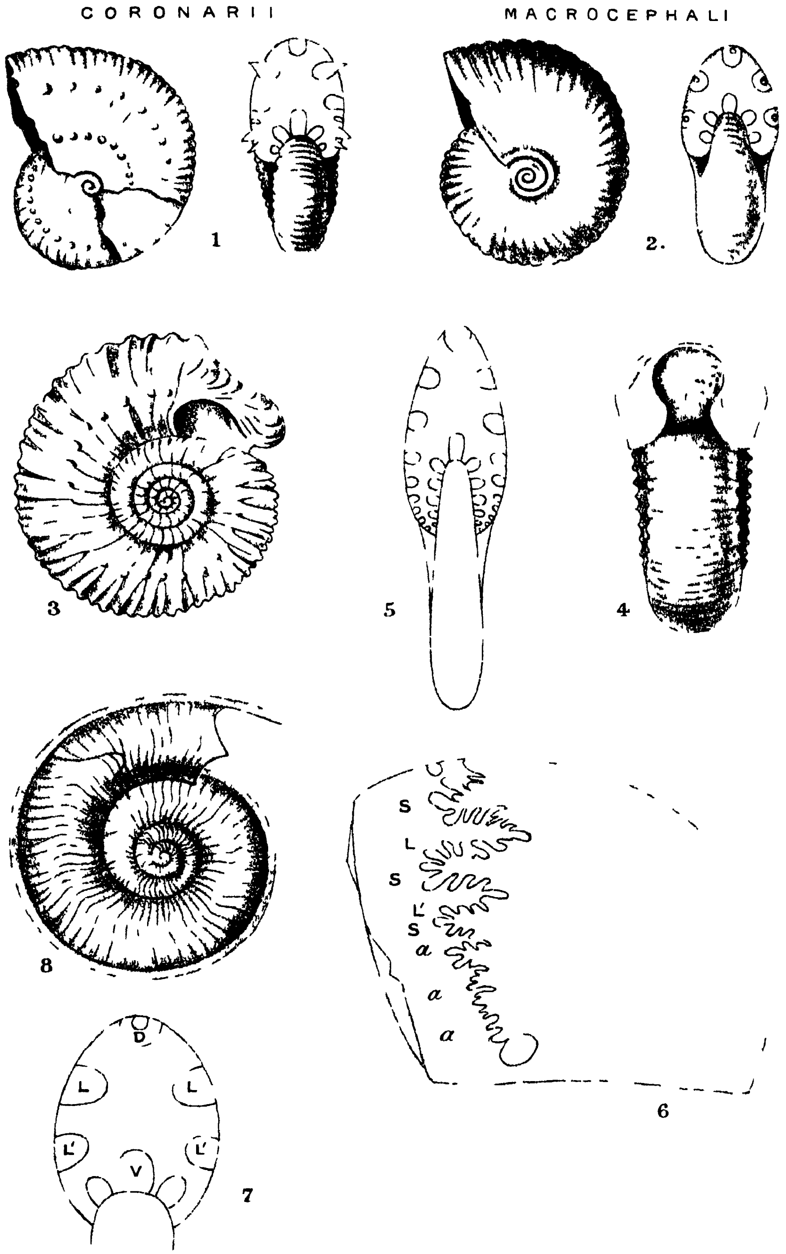
PLATE XLIII.

JURASSIC AMMONITES AND STRUCTURAL PARTS.

1. *Ammonites* (*Stephanoceras*) *Bechei* (Sow.). Middle Lias. Cheltenham and Lyme Regis.
   Group *Coronarii*. Fam. *Stephanoceratidæ*.
2. *Ammonites* (*Macrocephalites*) *macrocephalus* (Schloth.). Cornbrash and Oxford Clay.
   Group *Macrocephali*. Fam. *Stephanoceratidæ*.

3–4. *Ammo.* (*Stephanoceras*) *Braikenridgii* (Sow.). Inferior Oolite.
   Group *Coronarii*. Fam. *Stephanoceratidæ*.
   These two figures show the side and front view of the so-called labial prolongations, or complete mouth or aperture.

5. Front view of *Amm. heterophyllus*, showing the wall of one chamber with the position of the lobes and saddles (L.=Lobes, S.=Saddles, D.=Dorsal, and V.=Ventral lobes).
6. Side view of one suture of *Amm. heterophyllus*. (S., S., S.=Saddles, L.=First lateral lobe, L^1.=Second lateral lobe, *a.*, *a.*, *a.*=auxiliary lobes.) *Note.*—The circle at the lower end of the suture marks the umbilicus of the shell.
7. View of base of body-chamber of an ammonite with simple suture (D.=External lobe, V.=Inner lobe, L.=Lateral lobe, L^1.=Inferior lateral lobe).
   The intermediate spaces are occupied by the saddles.
8. *Ammonites* (*Harpoceras*) *serpentinus* (Rein.). Showing extension of the siphonal or ventral area, and sigmoidal folds or successive growth of the shell.



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JURASSIC AMMONITES AND STRUCTURAL PARTS.

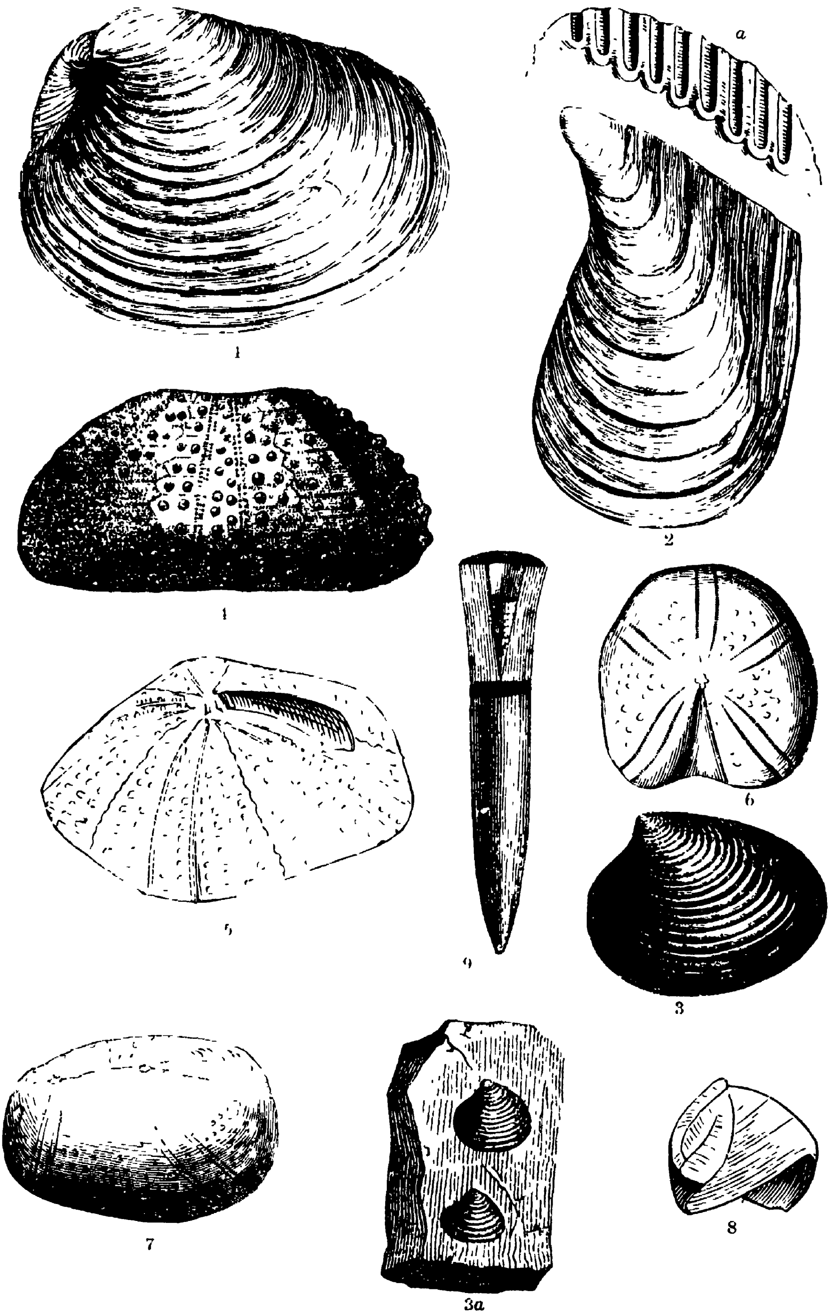
PLATE XLIV.

LOWER JURASSIC FOSSILS.

1. *Isocardia (Ceromya) concentrica* (Sow.). Inferior Oolite. Gloucestershire and Yorkshire.
2. *Perna quadrata* (Sow.). Cornbrash and Great Oolite. Gloucestershire, etc.
3. *Astarte elegans* (Sow.). Inferior Oolite. Somerset, Cotteswold Hills, Yorkshire.

3a. *Astarte Voltzii* (Hön.). Inferior Oolite.

4. *Pseudodiadema seriale* ?
5. *Pygaster semisulcatus* (Phill.). Inferior Oolite. Leckhampton, Crickley, Stroud, etc.
6. *Echinobrissus clunicularis* (Llhwyd.). Inferior Oolite. Wilts, Yorkshire, Dorset, Northampton.
7. *Collyrites bicordata* (Leske). Dorset, Somerset, etc.
8. *Rhynchonella cynocephala* (Richard). Inferior Oolite. Gloucestershire.
9. *Belemnites sulcatus* (Miller). Inferior Oolite. Dundry, etc.



LOWER JURASSIC FOSSILS.

Crustaceans and insects are numerous, the latter including many examples of beetles, moths, butterflies, dragon-flies, etc.

The *Great Oolite* proper was laid down in a shallow sea swarming with a prolific marine life, which included corals, bryozoans, sea-urchins, and starfish, all the inhabitants of clear sea-water; also—

Brachiopods,	including	*Rhynchonella, Terebratula, Magellania,* and *Crania.*
Lamellibranchs,	,,	*Pecten, Lima, Ostrea, Avicula, Astarte, Modiola, Pholadomya, Trigonia, Cardium, Arca, etc.*
Gasteropods,	,,	*Nerita, Nerinea, Patella, etc.*
Cephalopods,	,,	*Ammonites arbustigerus, A. subcontractus, etc.*
Reptilians,	,,	most of those in the Stonesfield Slate.

The *Forest Marble* attains a thickness of several hundred feet in Dorset, but thins out rapidly going northward. It is chiefly notable for its echinoderms, which include, among other species, the distinctive form *Apiocrinus elegans.*

The *Cornbrash* receives its name from the abundant crops of grain which are produced on its soils. It is a thin bed of earthy limestone varying from 5 to 40 feet thick, which, notwithstanding its insignificant dimensions that rarely exceed 20 feet, runs across the country from Devonshire to Yorkshire, and is therefore the most persistent member of the Lower Oolite Series or even of the Jurassic System.

Among the characteristic fossils of the Cornbrash are *Echinobrissus clunicularis* (Plate XLIV.), *Hinnites gradus, Cardium lobatum,* and the Cephalopods, *Ammonites* (*Clydoniceras*) *discus* and *A.* (*Macrocephalites*) *macrocephalus* (Plate XLIII. fig. 2).

Middle Oolite.

This division of the Jurassic System comprises two groups of beds—

$$\text{Middle Oolite}\begin{cases}\text{2. Corallian.}\\ \text{1. Oxfordian}\begin{cases}(b)\ \text{Oxford Clay.}\\ (a)\ \text{Callovian.}\end{cases}\end{cases}$$

Oxfordian.—This stage consists of two sub-stages, namely, the *Callovian* or *Kellaways Rock,* which is the lower sub-stage, and the Oxford Clay, the upper sub-stage.

The Callovian, also known as *Kellaways Rock,* which derives its name from the village of Kellaways, in Wiltshire, where this important subdivision was first described, is a calcareous sandstone, varying from 5 to 80 feet thick. It can be traced from Wiltshire to Lincolnshire, and northward into Yorkshire, where it is well developed.

The Callovian is chiefly notable for its fish remains, of which over 200 species have been identified; of these about one-third are found in the underlying Jurassic rocks, and about one-third pass upward into the overlying beds.

The fauna indicates a revival of the estuarine conditions that characterised the Estuarine Series of the northern counties in the Lower Oolite times; and contains, besides the fishes mentioned above, a considerable number of molluscs, among which we have *Ammonites, Belemnites,* the widely distributed *Gryphæa bilobata, Ostrea, Lima, Avicula, Lucina, Trigonia complanata, Cerithium abbreviatum,* and *Pleurotomaria guttata.*

The characteristic Ammonite of Kellaways Rock is *Ammonites* (*Sigaloceras*) *calloviensis.* The name *Callovian,* by which this zone is so commonly

known outside the British Isles, comes from Callovium, the Latin name of Kellaway.

Oxford Clay.—This great argillaceous deposit ranges throughout England from the coast of Dorset to Scarborough on the Yorkshire coast. It consists essentially of stiff clays and bituminous shales, and varies from 170 to 600 feet thick.

The muddy conditions of deposition of these sediments were obviously unfavourable for the growth of corals and bryozoans, which are rare, as also are echinoderms, which usually frequent clear water. Brachiopods and Gasteropods are not common, but the shallow-water Lamellibranchs that congregate in shell-banks are very abundant, and include *Gryphæa dilatata*, *Ostrea*, *Lima*, *Pecten*, *Avicula*, *Astarte*, *Trigonia*, *etc.*

Ammonites are numerous and *Belemnites* not uncommon, of the latter *B. Oweni* being the best known. The reptilian genera *Ichthyosaurus*, *Plesiosaurus*, and *Megalosaurus* are also present. Crustaceans and insects also occur, but plant remains are comparatively scarce.

Palæontologically the Oxfordian Series is divided into four Ammonite zones—

4. Zone of *Ammonites cordatus* (Plate XLII. fig. 3).
3. ,, ,, *Lamberti.*
2. ,, ,, *Jason.*
1. ,, ,, *calloviensis.*

The Corallian.—This is the upper division of the Middle Oolite. It consists mainly of shelly and oolitic limestones and calcareous sandstones, and is chiefly characterised by the presence of many corals. It extends from the coast of Dorset to Yorkshire. In some parts of Wiltshire the upper limestones have been replaced by valuable deposits of ironstone.

The corals mostly belong to the reef-building kinds, and, notably in Yorkshire, are found forming coral reefs in the positions in which they grew.

Sea-urchins are numerous and include *Cidaris*, *Hemicidaris intermedia*, and *Pygaster umbrella*. Among the Lamellibranchs, *Gryphæa*, *Ostrea*, *Lima*, *Pecten*, and *Avicula* are plentiful; also *Trigonia clavellata*, which is characteristic. *Ostrea gregaria* occurs in great numbers (Plate XLVI. fig. 2).

The principal Ammonites are *A. perarmatus* and *A. plicatilis*, both of zonal importance—

2. Zone of *Ammonites plicatilis*—Upper Corallian.
1. ,, ,, *perarmatus*—Lower Corallian.

Upper Oolite.

The three main subdivisions of the Upper Oolite are—

3. Purbeckian.
2. Portlandian.
1. Kimmeridgian.

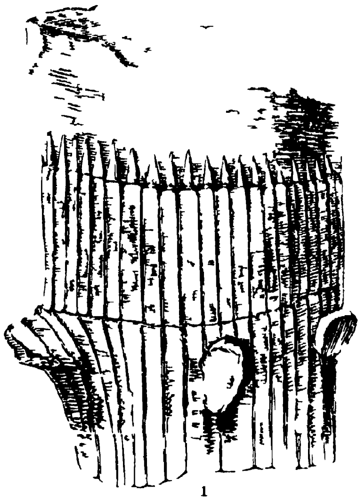
The Kimmeridgian.—The Kimmeridge Clay is one of the most persistent subdivisions of the Jurassic in England. It usually consists of dark-grey or black shaly clays, with frequent layers of septarian concretions. Occasionally the shales are calcareous and pass into bands of limestone. In the north of Scotland, on the east coast of Sutherlandshire, the beds are mostly sands, grits, and limestones.

PLATE XLV.

LOWER JURASSIC FOSSILS.

(Inferior Oolite.)

1. *Equisetites columnaris* (Brongn.). Inferior Oolite shale. Gristhorpe, etc., Yorkshire.
2. *Pterophyllum* sp. Inferior Oolite shale. Yorkshire coast.
3. *Nilssonia compta* (L. & H.). Inferior Oolite shale. Yorkshire.
4. *Tæniopteris vittata* (Brongn.). Inferior Oolite shale. Whitby, Gristhorpe, etc.



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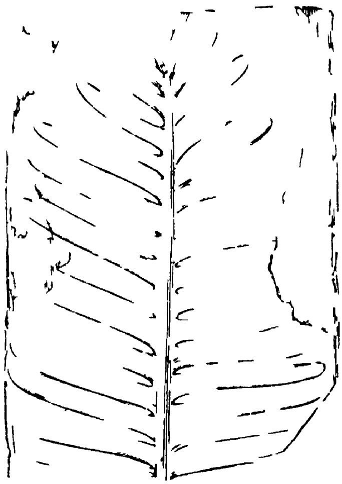

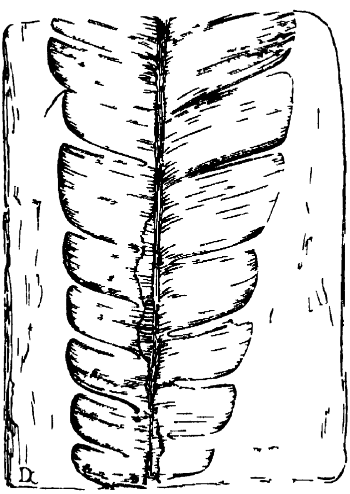

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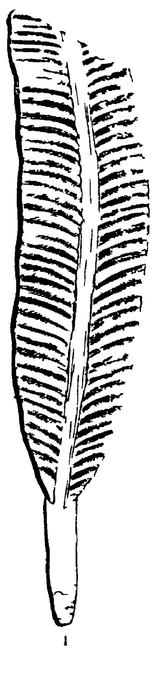


4

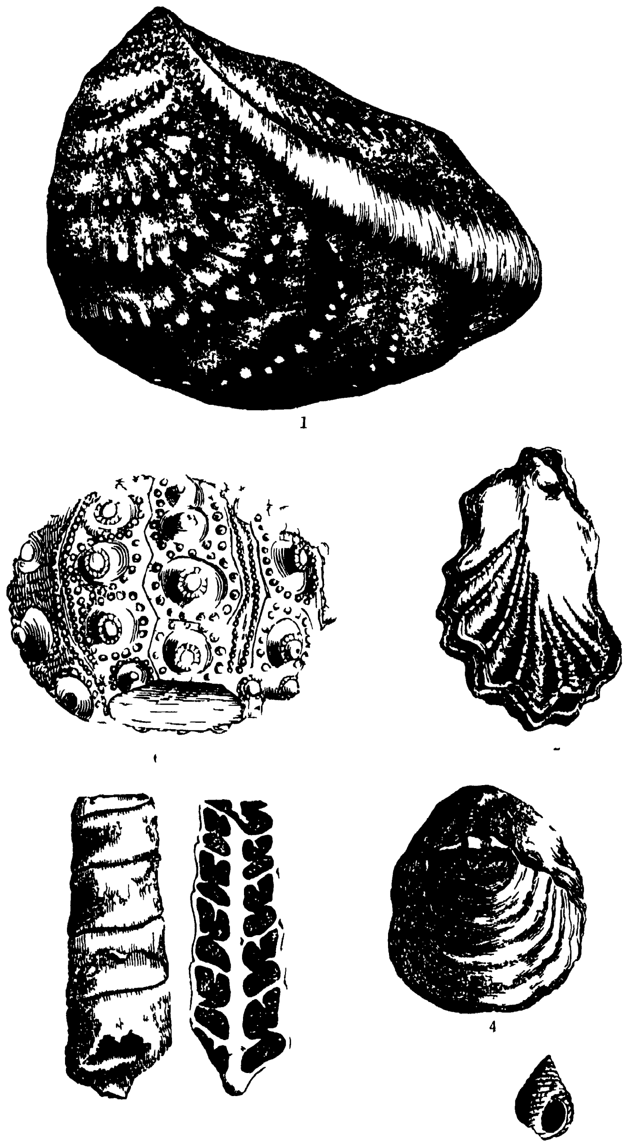
Lower Jurassic Fossils

(*Inferior Oolite*)

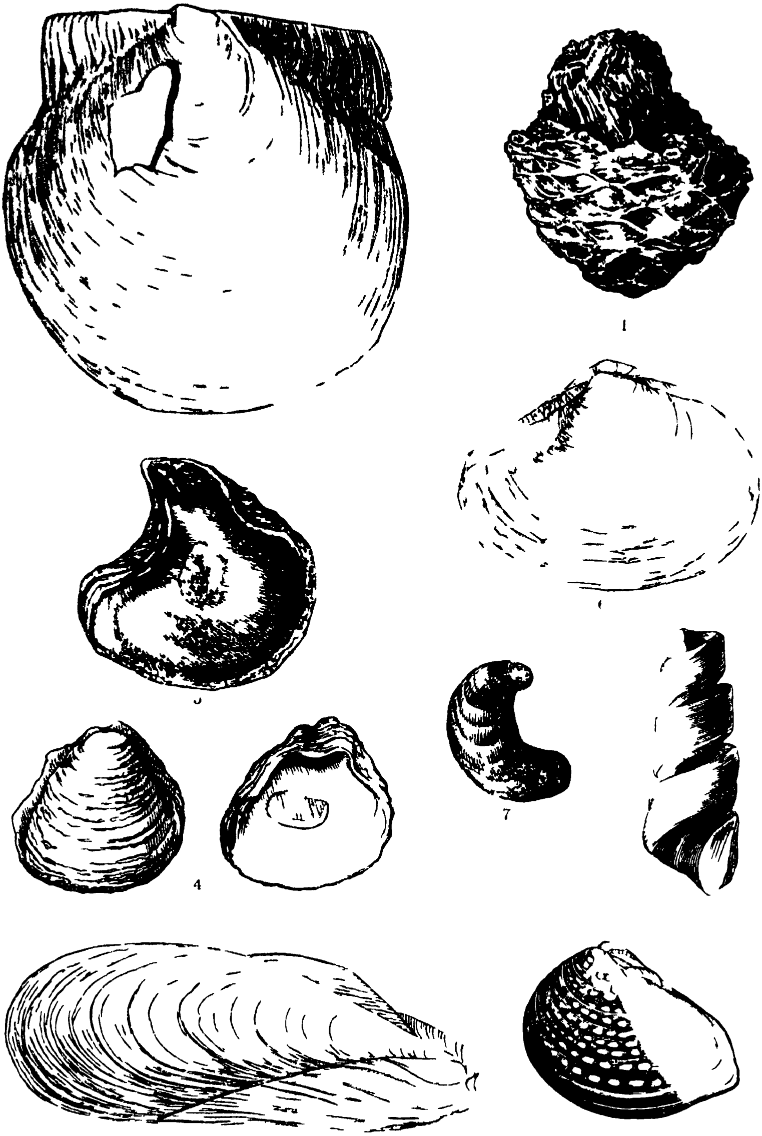
PLATE XLVI.

MIDDLE JURASSIC FOSSILS.

1. *Trigonia clavellata* (Park). Kimmeridge Clay and Portland Sand. Weymouth, Swindon, etc.
2. *Ostrea gregaria* (Sow.). Corallian beds. Yorkshire, Wiltshire, Cambridgeshire.
3. *Nerinæa Goodhallii* (Sow.). Corallian beds. Dorsetshire (Osmington, etc.).
4. *Gryphæa dilatata* (Sow.). Corallian and Oxfordian rocks. Wilts, Yorkshire, Oxfordshire, etc.
5. *Littorina muricata* (Sow.). Corallian beds. Wiltshire, Yorkshire, Cambridgeshire.
6. *Cidaris florigemma* (Phill.). Coral Rag. Calne, Yorkshire, etc



MIDDLE JURASSIC FOSSILS



UPPER JURASSIC FOSSILS

(*Kimmeridgian, Portland, Purbeck.*)

PLATE XLVII.

UPPER JURASSIC FOSSILS.

(Kimmeridgian, Portland, Purbeck.)

1. *Bucklandia nidiformis* (Brongn.). Dirt bed, Purbeck beds. Isle of Purbeck.
2. *Pecten lamellosus* (Sow.). Portland Oolite. Wiltshire, Dorset, Oxfordshire, etc.
3. *Cerithium portlandicum* (Sow.). Portland Oolite. Portland, Vale of Wardour.
4. *Ostrea expansa* (Sow.). Portland Oolite. Portland, Swindon, Quainton, etc.
5. *Ostrea deltoidea* (Sow.). Kimmeridge Clay. Portland, Weymouth, and *passim*.
6. *Thracia depressa* (Sow.). Kimmeridge Clay. Weymouth, Hartwell, Brill, etc.
7. *Exogyra virgula* (Defr.). Kimmeridge Clay. Aylesbury, Weymouth, etc.
8. *Modiola* sp. Portland Oolite.
9. *Trigonia gibbosa* (Sow.). Portland Oolite. Portland, Swindon, Vale of Wardour, etc.

The Kimmeridge Clay is well developed around Kimmeridge on the coast of Dorset, whence it extends northward to the Yorkshire coast. The thickness varies from 1200 feet in the South-West District to 100 feet in Oxfordshire.

The Kimmeridgian is everywhere richly fossiliferous, and was obviously laid down in a sea swarming with the peculiar marine life of shallow water. Hence corals and echinoderms are rare, and brachiopods are not common; but Lamellibranchs and Cephalopods are numerous, the former being represented by the characteristic species *Exogyra virgula* (Plate XLVII. fig. 7), *Ostrea deltoidea* (Plate XLVII. fig. 5), and *Astarte supracorallina*; and the latter by *Ammonites alternans*, *A. mutabilis*, and *A. biplex*.

The seas and estuaries still swarmed with reptilians, which included the marine plesiosaurs *Plesiosaurus* and *Pliosaurus*. The unwieldy and uncouth dinosaurs *Cetiosaurus*, *Pelorosaurus*, *Camptosaurus*, and *Megalosaurus* still herded in the marshy lands, while the crocodiles *Teleosaurus*, *Stenosaurus*, and others frequented the estuaries and deltas. The dolphin-like ichthyosaurs still inhabited the neighbouring seas, and the flying pterosaur *Pterodactylus* continued to dominate the air.

Palæontologically the Kimmeridgian is divided into two Ammonite zones—

2. Zone of *Ammonites biplex*=Upper Kimmeridgian.
1. „ „ *alternans*=Lower Kimmeridgian.

The Portlandian.—This series takes its name from the Isle of Portland, where it is typically developed. It follows the Kimmeridgian conformably, but has a narrower surface exposure, this, in the south of England, being mainly due to the overlap of the Upper Cretaceous. Further north from Bedfordshire to Norfolk, and in Yorkshire, no Portlandian beds are known, which may be due either to local uplift after the Kimmeridgian period or to denudation before the Cretaceous.

The Portlandian consists typically of marine limestones and sands, and the former encloses a rich fauna.

Corals are rare, and represented by one species, *Isastræa oblonga*. Brachiopods are also scarce. The most abundant fossils are Lamellibranchs, Gasteropods, and Cephalopods. In this formation the Ammonites attain a remarkable size.

Among the best-known molluscs in the Portlandian are the following:—

Lamellibranchs—*Trigonia gibbosa* (Plate XLVII. fig. 9).
Gasteropods—*Cerithium portlandicum* (Plate XLVII. fig. 3).
Cephalopods— *Ammonites giganteus*.

Fishes are represented by the persistent *Hybodus* and *Gyrodus*, while most of the reptilians of the Middle Jurassic are also present.

In the Isle of Portland and South-West England the Portlandian presents two distinct subdivisions, namely—

2. Portland Stone—Upper Portlandian.
1. Portland Sand—Lower Portlandian.

The *Portland Sand* consists of yellow, brown, and greenish sands, with occasional layers of clay and limestone; and the *Portland Stone*, of white shelly or oolitic limestone, with layers and nodules of chert.

The Purbeckian.—This series is typically developed in the Isle of Purbeck and in South-West England, and generally its distribution is coextensive with that of the underlying Portlandian with which it is everywhere closely associated. In most places it follows the Portlandian quite conformably,

but in some localities there is evidence of uplift at the close of that stage whereby some portions of the sea-floor became dry land and other portions shallow estuaries. This uplift by introducing terrestrial and estuarine conditions caused the migration from these areas of the marine life and reptilian forms that characterised the preceding Jurassic seas and shores.

The Purbeckian consists mainly of shales, marls, and limestones, with occasional beds of dark sandy clays containing much carbonaceous matter. These clays probably represent the soils of old land surfaces. They are locally called *Dirt Beds,* and in some places contain the trunks of cycads and conifers.

There is also a marine bed intercalated in the series composed almost entirely of the shells of the oyster *Ostrea distorta.* These shells impart a rough surface to the outcrops of the bed, which is in consequence frequently called the *Cinder Bed.*

Among the freshwater shells found in the Purbeckian Series, *Unio, Paludina, Physa,* and *Limnæa* are abundant. Insects are also plentiful and often beautifully preserved. Fishes are numerous, but reptiles are not common, and the forms present are mostly of the crocodilian type.

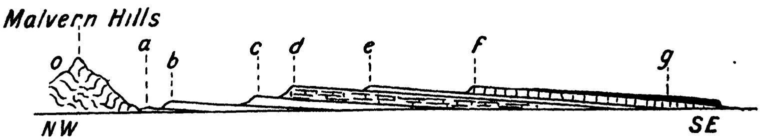


FIG 216A.—Showing arrangement of Mesozoic formations from Malvern Hills to coast of Essex.

(*o*) Pre-Cambrian gneiss.
(*a*) Trias.
(*b*) and (*c*) Lias.
(*d*) and (*e*) Oolites of Cotteswold Hills.
(*f*) Chalk of Chiltern Hills.
(*g*) Eocene of Essex.

The Purbeckian is chiefly celebrated for its mammalian remains, which are found at Durleston Bay in a stratum five inches thick in the middle of the series. The mammals belong to the marsupial order and include the genera *Plagiaulax* and *Triconodon.*

Jurassic in other Countries.

France.—Lithologically and palæontologically, the Jurassic in this region does not differ greatly from that of England except in the Mediterranean Province. The subdivisions recognised in France are as follows—

Oolite {
9. Portlandian.
8. Kimmeridgian.
7. Corallian.
6. Oxfordian.
5. Bathonian.
4. Bajocian.

Lias {
3. Toarcian.
2. Liassian.
1. Sinemurian.

Infra-Lias—Hettangian—Lies conformably on the *Avicula contorta* zone of the Rhætic.

Germany.—The subdivisions of the Jurassic recognised in North-West and Southern Germany are—

3. Upper or White Jura (=Malm).
2. Middle or Brown Jura (=Dogger).
1. Lower or Black Jura (=Lias).

The *Black Jura* is essentially an argillaceous formation and closely resembles the English Lias. It derives its name from the prevailing black colour of the shales which in the upper part of the series are so bituminous as to be a source of mineral oil.

The *Brown Jura* or *Dogger* corresponds to the English Lower Oolite division, with the exception of the *Callovian* sub-stage which German geologists include in the White Jura. It consists mainly of brown and yellow sandstones, dark clays, and shales with bands of oolitic ironstone.

The *Malm* or *White Jura* receives its name from the prevailing colour of the rocks, which consist mainly of limestones and marls.

The Jurassic rocks in Germany exhibit a close faunal relationship to the Jurassic of England, a correspondence which doubtless arises from the circumstance that England and Germany, in common with North France, lie in the *Central European Biological Province*, to which reference will be made later.

Russia.—Jurassic rocks cover a larger area in Russia than in any other part of Europe notwithstanding that the Lias and the Lower Oolite—that is, all below the Callovian—are absent. From this it would appear that Russia was dry land during the lower half of the Jurassic period.

The Jurassic fauna of Russia does not bear a close resemblance to that of England or Germany, which may arise from the fact that the Jurassic rocks of that region were deposited in a more northerly biological province or zone.

India.—There are two types of Jurassic rocks in India, namely, the *Marine* and the *Continental*.

The Marine type has an extraordinary development in Northern India, where it is represented by two facies in point of age, the *Alpine* and *Coastal*, the former comprising the Lower Jurassic rocks, the latter the Upper Jurassic.

The Alpine facies consists of massive beds of limestone which are developed on a vast scale in Baluchistan, in the Inner Himalayas, and in Tibet. The Coastal facies is met with in the Cutch, and Salt Range in the Punjab.

The succession of the Alpine Jurassic is interrupted by a break at the close of the Callovian stage arising from uplift; and deposition did not again begin in this region until about the end of the Jurassic or beginning of the Cretaceous period. The Liassic and Lower Oolitic rocks are well represented; and the principal Ammonite zones of Central Europe and England have been identified in the black limestones of Baluchistan, in which they follow the same chronological succession.

In the Coastal facies the Lias and Lower Oolite are absent, showing that, at the time a sea-floor existed in the North Himalayan and Tibetan areas, dry land occupied the Cutch. When deposition began in the Coastal area, the Alpine area emerged from the sea.

In the matter of age, the Jurassic rocks of the North Himalayan and Tibetan regions exhibit a singular contrast with those of the Cutch, the stages present in the coastal region being absent in the extra-peninsular, and the converse. Obviously subsidence in the one region was compensated by uplift in the other.

The *Continental type* of the Jurassic System of India is represented by the Upper Gondwana, which consists mainly of sandstones and shales with

coal-seams and bands of limestone. In the Rajmahal Hills the rocks are intercalated with massive sheets of basalt.

The Rajmahal Shales contain a rich fossil flora which includes an abundance of ferns and cycads, the latter being represented by *Ptilophyllum*, and the former by *Tæniopteris* and *Dicksonites*.

During the Jurassic period the Himalayan region of Northern India was a sea-floor; and so far as the available evidence will permit us to judge, it would appear that the continent from which the Jurassic sediments were derived lay to the south and south-east. This continent, of which the Peninsular area formed a part, was the Gondwana Land of Indian geologists.

North America.—Jurassic rocks are not found in the Eastern States, but are well developed in California, Sierra Nevada, and Alaska; and also in the States of Wyoming, Utah, Dakota, and Colorado, where they have yielded a remarkable group of dinosaurs, tortoises, pterodactyls, crocodiles, and lizards, the latter including some forms related to the living *tuatara* (*Sphenodon punctatum*) of New Zealand. The dinosaurs were herbivorous, and among the principal genera distinguished by Marsh are *Atlantosaurus*, *Brontosaurus*, and *Stegosaurus*.

Associated with these reptilian remains, there have also been found many genera of small marsupial mammals, including the genera *Allodon*, *Docodon*, *Tinodon*, and many others.

In California the thickness of the Jurassic rocks is about 2000 feet, part of which is volcanic tuff; and in Nevada, 5000 or 6000 feet, the upper 4000 feet of which are slates, the remaining lower beds being limestones.

In these states the Jurassic rocks are sharply folded and frequently much metamorphosed. The fauna of the Callovian and Oxfordian in this region shows a relationship to that of the Central European Biological Province, while the Kimmeridgian is of a more Russian facies. Generally speaking, the Jurassic System plays a subordinate part in the geological structure of North America, the greater portion of which was dry land from the close of the Triassic till the Cretaceous.

Australasia.—Jurassic rocks have been identified in Borneo, the Moluccas, and New Guinea, whence they extend southward to Queensland, New South Wales, Victoria, South Australia, and New Zealand.

In the Australian Continent the rocks for the most part consist of sandstones (greywackes), shales, and conglomerates of the continental facies, though marine beds are not totally absent. The continental beds are distinguished by the presence of fossil plants, reptilian and fish remains.

A characteristic and widespread fern is *Tæniopteris daintreei*; but the succession of the Jurassic rocks has not yet been worked out in detail.

In New Zealand the Jurassic rocks consist of two types, the Coastal and Alpine. The rocks of the coastal type contain thin seams of bituminous coal and occasional bands of estuarine sandstones and shales. Plant remains are abundant and include *Tæniopteris*, *Pecopteris*, *Sphenopteris*, *Equisetites*, *Coniopteris*, *Araucarites*, *Elatocladus*, *Pagiophyllum*, and *Stachyotaxus*. The molluscs are mostly those found in shallow seas and estuaries. They include *Pecten*, *Lima*, *Avicula*, *Ostrea*, *Pinna*, *Modiola*, *Ammonites*, and *Belemnites*.

The Jurassic rocks of the Alpine type are mainly developed in the Alpine Chain, where they attain a thickness exceeding 10,000 feet. They consist of a vast pile of alternating greywackes and shales of the *Flysch* facies, and, so far as known, are devoid of all fossils. They appear to have been formed in the delta of a river which may have drained the southern portion of the ancient Gondwana Land.

Calcareous rocks are conspicuously absent in the Jurassic System, as developed in Australia and New Zealand.

Antarctic Continent.—Sandstones and shales of Trias-Jura age occur on the north-west side of Graham's Land, in the Antarctic region. They contain a rich and varied flora embracing ferns, cycads, and conifers. Among the plants are the genera *Sagenopteris, Thinnfeldia, Cladophlebis, Pterophyllum*, and *Otozamites*, all of which are found in the older Mesozoic rocks of Northern India and Eastern Australia, and some are found in the Argentine.

The presence of these plants would indicate a mild and moist climate during the Jurassic period, where now the land is covered with permanent ice and snow.

Zonal Distribution of Faunas.—As the faunas become more highly organised and differentiated, they are increasingly subject to the influences of climatic conditions; and the tendency of progressive biological development is to bring into existence forms adapted to their peculiar environment.

There is not much evidence till we reach the Jurassic period, that the distribution of the marine inhabitants was influenced by climatic conditions. But in the faunas of the marine limestones and marls of this period there is some evidence that the climatic or faunal zones, which are so characteristic of the present time, had already been established.

At one time it was believed that the Jurassic faunas of Europe could be divided into three climatic zones encircling the globe in a direction parallel to the equator. But recent observations have shown that the zonal arrangement is violated by many exceptions. It has been found that where deposits at the equator are similar to those of Central Europe, the fossils are similar.

In geological times later than the Jurassic, the faunas in similar climatic zones show a biological relationship in the corresponding latitudes in each hemisphere.

In Europe, where the Jurassic faunas have been studied more closely than elsewhere, Neumayr has distinguished three Jurassic marine provinces characterised by different faunas—

(1) *The Mediterranean Province,* which includes the deposits of the Balkan Peninsula, Alps, Carpathians, Cevennes, Italy, Spain, Crimea, Caucasus, Asia Minor, and Further India.

(2) *The Middle European Province,* which includes the extra-Alpine Jurassic of France, the Swiss Jura, Germany, the Jurassic of England, North-West Spain, Portugal, the Baltic Region, Japan and California.

(3) *The Russian or Boreal Province,* which includes the Jurassic rocks of Central and Northern Russia, Nova Zembla, Spitzbergen, Greenland, and Alaska.

Each zone is believed to be distinguished by certain Ammonites and other fossils. These *isozoic zones* were presumed by Neumayr to coincide with the climatic zones—

The *Mediterranean Province*=the *Alpine, Equatorial,* or *Tropical Zone.*
The *Middle European Province*=the *Temperate Zone.*
The *Russian or Boreal Province*=the *Arctic* or *Boreal Zone.*

The Jurassic faunas of the Southern Hemisphere occur in the same isozoic zones as in the Northern. For example, the Jurassic faunas of South Australia, New Zealand, Cape Colony, Chile, Bolivia, Peru, and Argentine, exhibit a striking resemblance to the Jurassic faunas of England and Swabia.

The *Equatorial Zone* is characterised by the extraordinary development of

Ammonites of the genera *Phylloceras*, *Lytoceras*, and *Simoceras*; and of the brachiopods, *Terebratula diphya* is peculiar to this province.

In the so-called Temperate Zone *Phylloceras* and *Lytoceras* are not common, while *Harpoceras*, *Aspidoceras*, and *Oppelia* are very abundant. Coral reefs are prominent and frequently of great extent and thickness.

In the so-called *Boreal Zone* the Ammonite genera *Harpoceras*, *Lytoceras*, and *Phylloceras* are entirely absent, and coral reefs are unknown. On the other hand, an Ammonoid *Cardioceras* and the Lamellibranch *Aucella* are characteristic and widespread

Economic Products.—The Triassic of Western Europe contains considerable beds of oolitic iron ore Well known also are the deposits of this type occurring in Lorraine

CHAPTER XXXI.

CRETACEOUS SYSTEM.

THE Cretaceous is the youngest of the three great systems into which the Mesozoic is divided. It received its name in England from its most important member the *Chalk*, for which the Latin name is *creta*.

The Cretaceous System is world-wide in distribution, and embraces a considerable variety of sandy, clayey, and calcareous deposits.

At the close of the Jurassic, the form of the great continents was already clearly outlined, except the regions now occupied by the young mountain-chains; hence the Cretaceous sediments were laid down for the most part in seas marginal to the existing continents, or in land-locked estuaries and basins to which the sea had free access. As a result of this marginal distribution, the deposits of this period are frequently covered over to a considerable extent with the succeeding Tertiary formations, which were also laid down as marginal sheets mantling round the shores of the continents and larger islands.

Rocks.—The prevailing rocks are sands, clays, shales, and limestones, but the deposits frequently exhibit considerable local variations due to differences in the conditions of deposition Even the *Chalk*, which is so prominent and important in England, North France, Belgium, Baltic area, and North America, is absent in Central Germany, Alps, Africa, and Australia.

The lower members of the system in North-West Europe are frequently sandy beds of terrestrial and estuarine origin with plant remains and seams of coal. Following these come alternating sandy and clayey deposits of marine origin frequently containing lines of septarian concretions; and in their turn these are succeeded by chalk and other calcareous beds which in many regions close the succession, but in others are followed by estuarine and terrestrial deposits with coal-seams.

The sandy beds of both hemispheres are frequently dark green in colour, due to the presence of glauconitic grains. Though common in Cretaceous formations in many parts of the globe, glauconitic sands are not confined to that epoch. They are plentiful in the Lower Tertiary marine systems everywhere, and were doubtless as abundant in the Palæozoic, though not now recognisable as such on account of the alteration they have undergone. The iron of many ancient ironstone deposits was probably derived from glauconitic-bearing beds.

Glauconitic deposits are believed to have been formed in warm seas of moderate depth, *i.e.* from 100 to 200 fathoms, where there was little terrigenous matter being deposited, but where Foraminifera abounded.

Cretaceous Transgression of the Sea.—In both hemispheres the Upper Cretaceous seas advanced over the low-lying maritime lands of all the continents, and this unprecedented transgression was so universal that the Upper Cretaceous sediments extend far beyond the limits of the Lower Cretaceous,

and rest on the worn-down surfaces of the older formations on which they trespass in some regions for thousands of square miles. It has been urged, that the so-called Cenomanian transgression (E. Suess) was not a sudden event, but started at different times in different regions, and that there are recessions of the era in certain areas that correspond to the advance of the sea over other land-masses.

The great transgression may have arisen from some profound crustal disturbance, perhaps the collapse of the Gondwana continent that is supposed to have occupied the present site of the Indian and South Pacific Oceans, from the Permian till the Cretaceous; or it may have been caused by the sudden melting of the polar ice.

Relationship between Cretaceous and Tertiary.—Though the stratigraphical unconformity between the Latest Cretaceous and the Eocene is often so slight as to be imperceptible, the faunal break is the sharpest known in the Earth's history. In the interval between the Cretaceous and Tertiary, normal denudation and normal deposition must have gone on uninterruptedly, and at the same time the seas and land must have swarmed with life. Though the Upper Cretaceous and the Eocene are strongly developed in both hemispheres, the strata that are claimed to bridge the Cretaceo-Tertiary hiatus are represented by only a few estuarine and lacustrine deposits containing a scanty life.

The sudden disappearance of most of the characteristic Cretaceous genera before the advent of the Eocene may be traceable to climatic and geographical changes arising from the recession of the sea. If the sea retreated to the edge of the continental shelf, the marine faunas would be forcedinto new and perhaps uncongenial environments, which would lead to the extinction of many old genera and species and to the development of new species.

In accordance with this simple explanation the sediments of the Cretaceo-Eocene interval were deposited in the abyssal depths that lie beyond the edge of the shelf.

The universal recession of the sea at the close of the Cretaceous may have been caused by some diastrophic movement of the crust, or by the growth of the polar ice caps.

At the close of the Cretaceous, the long era of quietude and immunity from volcanic disturbance was broken by the revival of eruptions on a gigantic scale; and since that date volcanic activity of a more or less intense kind has been in evidence in some part of the globe up to the present day.

From the above it would appear that the Cretaceous deposits were laid down on a slowly sinking sea-floor until the middle of the period, when a sudden invasion of the sea took place. Thereafter, subsidence continued in many regions until the close of the Chalk, when the uplift began which eventually led to the deposition of the estuarine and terrestrial deposits of the uppermost beds of the Cretaceous.

Distribution.—The Cretaceous is found in all the great continents. It is one of the most extensively developed of all the rock-systems, and in some regions covers hundreds of thousands of square miles in one continuous sheet.

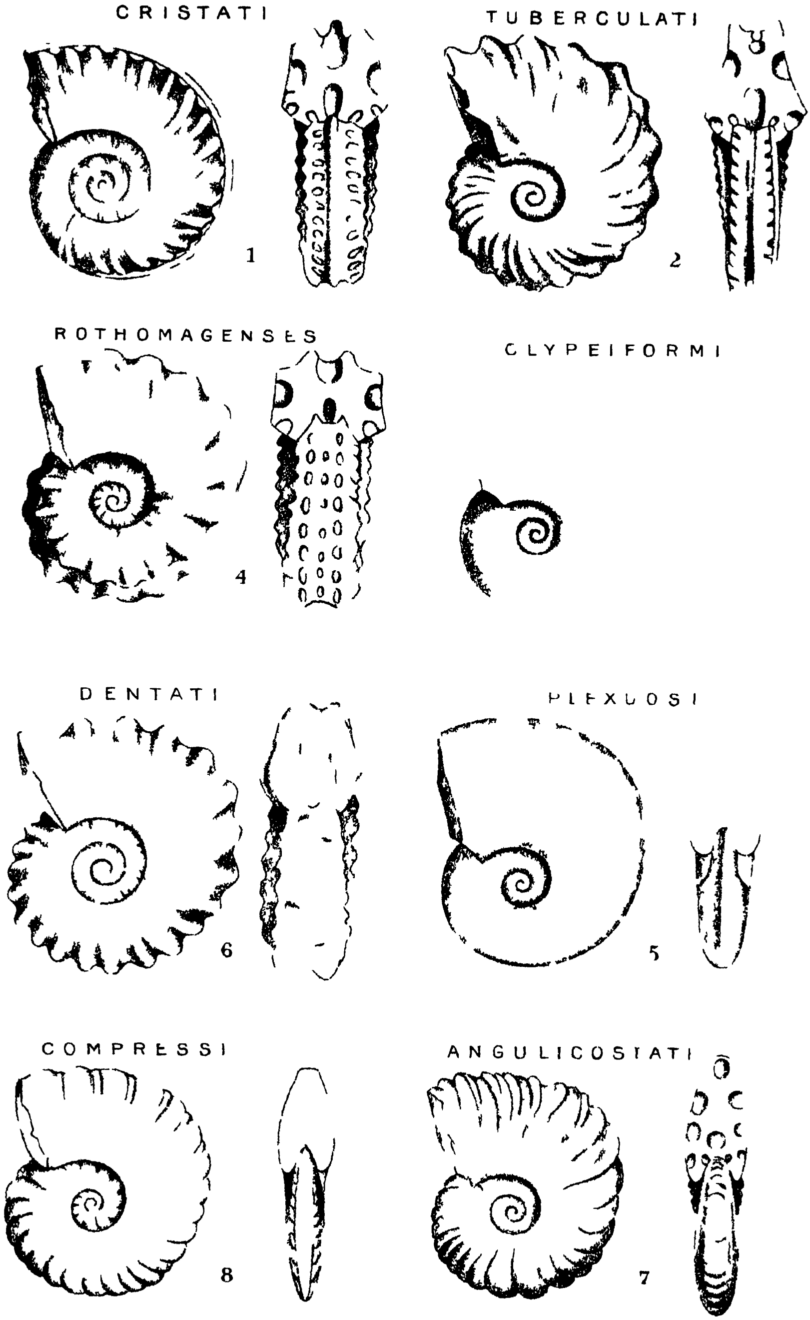
In Europe the Cretaceous presents two distinct palæontological facies, the Central European and Mediterranean. The Central European is well developed in England, North France, Belgium, North Germany, Bohemia, and Baltic area; and the Mediterranean type on both sides of that basin, in Portugal, Spain, South France, Italy, Switzerland, Sicily, Greece, Carpathians, Morocco, Algiers, Tunis, Egypt, Syria, and Palestine.

The Mediterranean facies also stretches eastwards into Asia, and covers

PLATE XLVIII.

CHARACTERISTIC CRETACEOUS AMMONITES.

1. ***Ammonites* (*Schlœnbachia*) *rostratus*** (Sow.). Upper Greensand and Gault. Devizes and Folkestone.
   Group *Cristati.* Fam. *Prionotropidæ.*
2. ***Ammonites* (*Hoplites*) *lautus*** (Sow.). Gault and Upper Greensand.
   Group *Tuberculati.* Fam. *Cosmoceratidæ.*
3. ***Ammonites clypeiformis*** (Sow.). Upper Greensand.
   Group *Clypeiformi.*
4. ***Ammonites* (*Acanthoceras*) *Rhotomagensis*** (Brongn.). Chalk Marl and Lower Chalk.
   Group *Rhotomagenses.* Fam. *Cosmoceratidæ.*
5. ***Ammonites* (*Leopoldia*) *Leopoldianus*.** Neocomian.
   Group *Dentati.* Fam. *Cosmoceratidæ.*
6. ***Ammonites* (*Hoplites*) *interruptus*** (Sow.).
   Group *Dentati.* Fam. *Cosmoceratidæ.*
7. ***Ammonites* (*Hoplites*) *Deshayesii*** (Leym.). Upper Neocomian.
   Group *Angulicostati.* Fam. *Cosmoceratidæ.*
8. ***Ammonites* (*Pulchellia*) *catillus*** (Sow.). Upper Greensand.
   Group *Compressi.* Fam. *Pulchellidæ.*



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CHARACTERISTIC CRETACEOUS AMMONITES.

enormous tracts in Asia Minor, Persia, Arabia, Afghanistàn, Baluchistan, Northern Himalayas, Tibet, and China.

The Cretaceous System is also present in Japan, Australia, New Zealand, Antartic region E. of Graham's Land, Patagonia, Chile, Peru, Bolivia, United States, British Columbia, Alaska, and Greenland. In the North American continent the northern and southern facies are as well marked as in Europe.

From this biological relationship we know that the Cretaceous sea extended from the Atlantic eastward through the Mediterranean area to Asia Minor, Persia, and India ; and during the great transgression spread over the greater part of the desert area of North Africa. From the North Atlantic long arms of the Cretaceous sea extended through Germany and Baltic area. The distribution of the Cretaceous shows that a continuous sea existed along the west coast of America from Alaska to Patagonia.

In the West Atlantic a broad prolongation of the sea stretched northward from the Mexican and Gulf borders, spreading over the Great Plains to the Arctic Ocean.

Flora.—The earliest Cretaceous flora is closely related to that of the Jurassic, and ferns, cycads, and conifers are still the dominant forms of vegetation ; but there was a remarkable change impending in the character of the land vegetation, and in the Upper Cretaceous we witness the world-wide appearance of the angiosperms, both monocotyledons and dicotyledons, which represent the highest forms of vegetation prevailing at the present time.

The advent of mammals and other highly organised vertebrates a full geological period ahead of the less delicately organised angiosperms is a biological puzzle the solution of which is not very obvious.

Fauna.—Many of the Jurassic genera appear in the Cretaceous together with new forms, and generally we may say that the fauna is stamped with a distinctly Mesozoic facies.

Foraminifera are exceedingly abundant as builders of chalk and other limestones, the most common genera being *Globigerina* and *Orbitolina,* the former characteristic of the true chalk of North-West Europe, the latter of the Alpine Cretaceous.

Calcareous sponges are common in the middle of the system, and siliceous sponges abound in the Chalk.

Corals of the reef-building type are rare. Widespread genera of simple form are *Parasmilia, Micrabacia,* and *Trochocyathus,* the last well known also in the Lower Tertiary of both hemispheres, and still now living.

Sea-urchins are numerous in the Chalk, the genera *Micraster, Holaster, Hemiaster, Echinobrissus,* and *Cidaris* being common. A few starfishes are known ; and crinoids are represented by the genus *Marsupites.* Polyzoans are common in the Calcareous division.

Brachiopods are abundant, and include *Terebratula, Terebratella Magas, Rhynchonella,* and *Crania*—all living genera.

Molluscs are well represented. Among the common Lamellibranchs are *Inoceramus, Exogyra, Ostrea, Trigonia, Gervillia,* and *Spondylus,* as well as the curious genus *Hippurites,* which forms massive beds of limestone in the Alpine facies of Southern Europe. Of these *Inoceramus, Exogyra,* and *Hippurites* are distinctively Cretaceous, and the last is limited to this system.

The shell of *Inoceramus* is composed of aragonite built up of fibrous layers lying at right angles to the axis of the shell, which is consequently very fragile. Fragments of *Inoceramus* are common in the Chalk. Some Inocerami attained a length of two or three feet, their gigantic size being an indication of genial seas and a plentiful food supply.

Of Gasteropods, the genera *Pleurotoma*, *Aporrhais*, *Rostellaria*, *Cerithium*, and *Fusus* are abundant.

Cephalopods swarmed in the Cretaceous seas, and are chiefly represented by Ammonites and Belemnites which make their last appearance. The Ammonite genera are specially characterised by the free-whorled (*Crioceras*, Plate L. fig. 4), hooked (*Hamites*, fig. 217), and horn-shaped and turreted (*Turrilites*, fig. 218) forms, many of which possessed beautifully ornamented shells.

In the Upper Cretaceous the place of the true Belemnites is taken by *Belemnitella* and its sub-genus *Actinocamax*. The genus *Nautilus*, the most persistent of all Cephalopods, is represented by many species in the Upper Cretaceous, some of large size.

Fishes were common in the Cretaceous seas and rivers, and included many

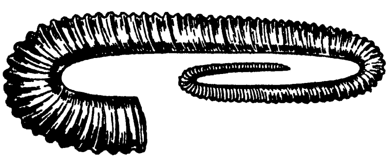


FIG. 217.—Hamites.

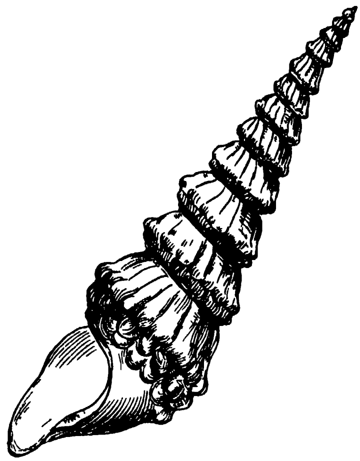


FIG 218.—Turrilites.

Teleosts (bony fishes) which became very plentiful towards the close of the period.

The reptilians *Ichthyosaurus*, *Plesiosaurus*, and *Pterosaurus*, which dominated the vertebrate life of the Jurassic, are seen for the last time in the Cretaceous.

The huge dinosaurs reach their maximum development in this period, and disappear at its close. They are specially represented by *Iguanodon* *Megalosaurus*, and the gigantic pythonomorph *Mosasaurus*, one of the extinct monsters of the Cretaceous seas, is estimated to have attained a length of 75 feet. The Cretaceous rocks of the Western States of North America have yielded a rich harvest of dinosaurs, pterosaurs, crocodilians, sea-saurians, turtles, and sea-serpents.

Perhaps no less remarkable than the dinosaurs are the toothed birds of the Cretaceous of Kansas, among the most interesting of which is *Ichthyornis victor*. The only bird remains found in the English Cretaceous are those of the genus *Enaliornis*.

With the dinosaurs, crocodiles, and other reptilians found in the Upper Cretaceous rocks of Dakota and Wyoming, there have been found numerous jaws and teeth of small marsupial mammals related to the Jurassic and Triassic forms.

Subdivisions.—The subdivisions of the Cretaceous System in England where the succession was first accurately determined, with the names of the corresponding subdivisions in North France, which are now commonly used as stage or time-names for the different groups of beds, are as follows :—

		England.	France.
Upper Cretaceous		Absent, . .	Danian.
	5. Chalk	Upper Chalk,	Senonian.
		Middle Chalk,	Turonian.
		Lower Chalk	Cenomanian.
	4. Upper Greensand, . .		Cenomanian.
	3. Gault, ...		Albian.
Lower Cretaceous	2. Lower Greensand, . .		Aptian.
	1. Wealden	Weald Clay	Neocomian.
		Hastings Sand	Neocomian.

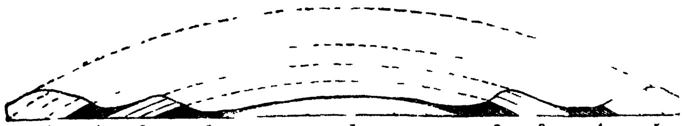


FIG. 219.—General section across Wealden.

1, Hastings Sand. 2, Weald Clay. 3, Lower Greensand. 4, Gault. 5, Upper Greensand and Chalk.

BRITISH ISLES.

The Cretaceous rocks of England occur in three distinct areas, namely the Southern, Middle, and Northern. In the Southern District the deposits are mainly freshwater ; in the Middle District where the lower members are absent, marine ; and in the Northern District, marine.

In the Southern District they occupy almost the whole of the central portion of the Wealden Dome lying between the North and South Downs. They also appear in the Isle of Wight, where they are tilted at high angles (fig. 219A), in the Isle of Purbeck, and near Weymouth, but these outcrops are subordinate in extent to that in the Weald, which is the largest and most important development in the Cretaceous in England or in the British Isles.

The Cretaceous rocks of the Middle District are chiefly developed in Bedfordshire and Cambridgeshire.

The Northern District extends from North Norfolk to Flamborough Head, and in this area the Cretaceous System is best displayed in Lincolnshire and Yorkshire.

The Cretaceous rocks fall into two great natural divisions : the Lower Cretaceous, well displayed in the Southern and Northern Districts ; and the Upper Cretaceous, found in each of the three geographical areas referred to above.

Lower Cretaceous.

SOUTHERN DISTRICT.

The Lower Cretaceous of the south, which is freshwater, is quite unlike the Lower Cretaceous of the north, which is marine and palæontologically shows a relationship to the Lower Cretaceous of the Baltic area.

While freshwater basins existed in the south of England, and the Middle District formed dry land, a sea existed in the Northern District. But when subsidence took place, the southern sea invaded the freshwater basins, and encroached on the Middle District. Thereafter there was a continuous sea from south to north, and the fauna of the southern sea spread northward till it reached the Northern District.

Wealden (Neocomian).—This is a freshwater series that derives its name from the Weald of Sussex, Surrey, and Kent, where it is typically developed. It is overlain conformably by the Lower Greensand.

The Wealden comprises two main groups, namely—

2. Weald Clay.
1. Hastings Sand.

The total thickness of the Wealden Series is over 2000 feet, of which the Weald Clay comprises about 1000 feet. The conditions of deposition were deltaic, and the sediments were apparently laid down during a period of slow but progressive subsidence.

The Wealden flora includes ferns, cycads, and conifers. Among the ferns are *Sphenopteris* and *Alethopteris*. The molluscs include the freshwater forms *Unio valdensis* (Plate XLIX. fig. 1), *Cyrena media* (Plate XLIX. fig. 2), *Viviparus fluviorum*, and a few littoral shells, including *Mytilus*, *Exogyra*, and *Ostrea*.

Among the fish we have *Lepidotus Mantelli*, a ganoid related to the gar-pike of the North American rivers. Reptilians are abundant and represented by plesiosaurs, dinosaurs, and flying pterodactyls. Among the dinosaurs, the gigantic *Iguanodon* was common.

The local subdivisions of the Wealden are as follows:—

Wealden (Deltaic)	2. Weald Clay		Neocomian.
	1. Hastings Sand	*c.* Tunbridge Wells Sand	
		b. Wadhurst Clay	
		a. Ashdown Sand	

Lower Greensand.—This is the upper division of the Lower Cretaceous. The progressive subsidence of the Neocomian, which affected the whole of North-West Europe, enabled the sea to encroach on the Wealden Delta where the marine sediments of the Lower Greensand were laid down conformably following the Weald Clay.

The stages of the Lower Greensand are as follows:—

Lower Greensand	Folkestone Beds	Mainly Aptian.
	Sandgate Beds	
	Hythe Beds	
	Atherfield Beds	

The rocks of this series consist of grey, yellow, and green sands intercalated with beds of clay, limestone, and ironstone. The green-coloured sands, from which this division derives its name, owe their prevailing green hue to the presence of glauconitic grains.

Some of the calcareous bands, notably those in the Hythe stage, pass into more or less compact limestones, such as that locally called *Kentish Rag*, which is extensively used as a building-stone and for burning into lime.

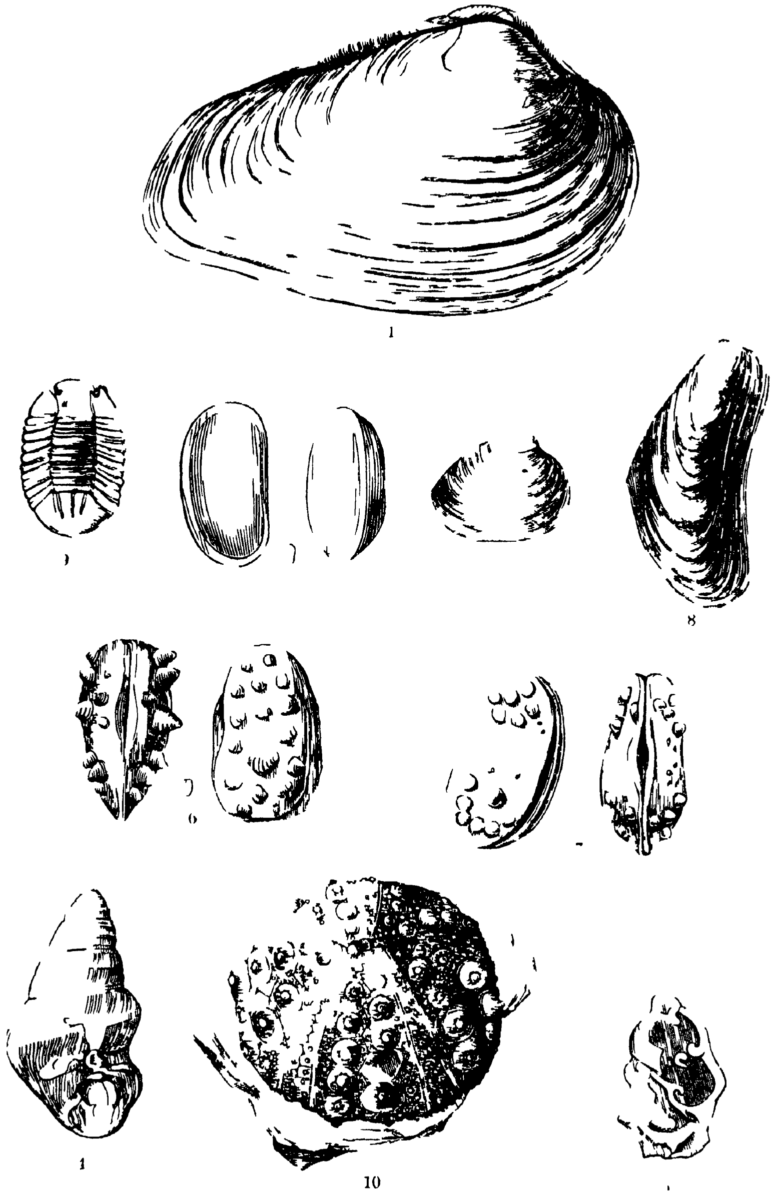
Lower Greensand contains a large assemblage of molluscs, among which littoral shells are conspicuous. The most common forms are *Ostrea*, *Exogyra*, *Perna*, and *Arca*, with which are associated many Ammonites and Belemnites.

Among the characteristic species are *Terebratula sella*, *Exogyra sinuata*

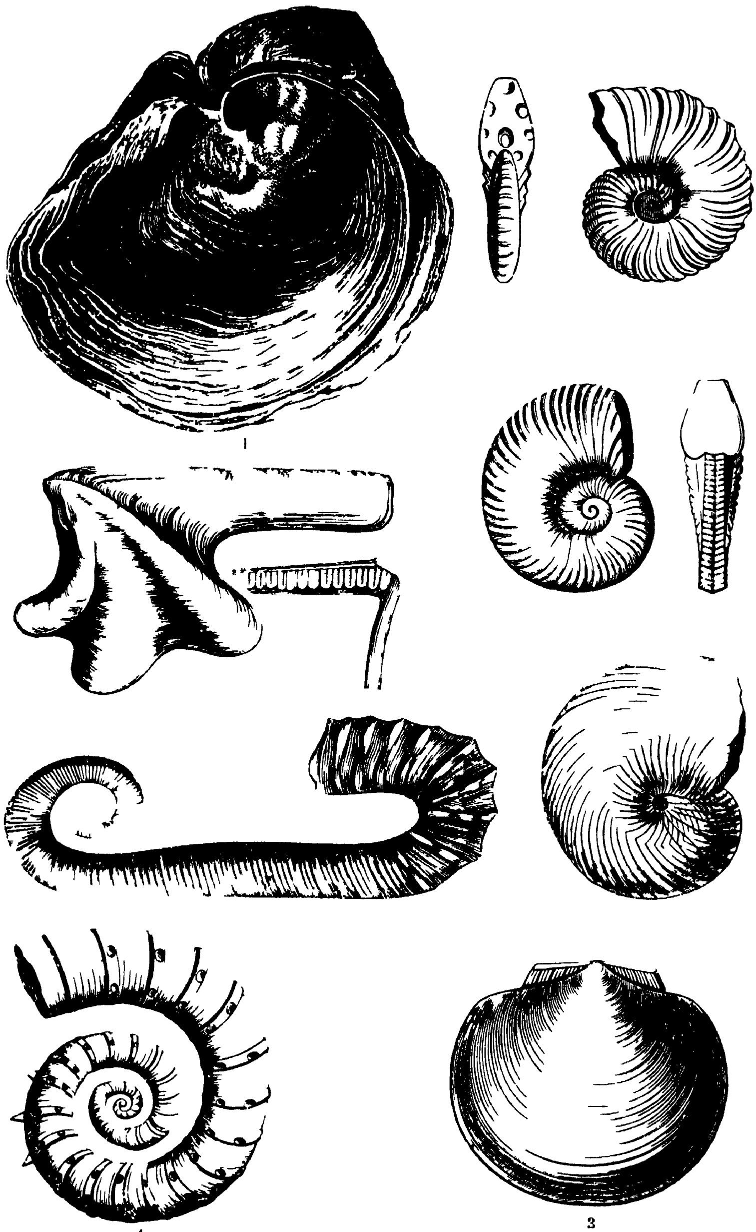
PLATE XLIX

PURBECK AND WEALDEN FOSSILS.

1. *Unio waldensis* (Mant.). Hastings Sand, etc. Wealden, Isle of Wight, Hastings.
2. *Cyrena media* (Sow.) Weald Clay. Kent, Surrey, Sussex.
3. *Cypridea waldensis* (Sow.). Weald Clay. Isle of Wight, Tunbridge Wells, Dorset.
4. *Vicarya lujani* (de Verneuil). Punfield beds and Upper Neocomian. Isle of Wight and Punfield.
5. Vertical section of same, showing ridges.
6. *Cypridea tuberculata* (Sow.). Upper Purbeck beds.
7. *Cypridea fasciculata.* Middle Purbeck beds.
8. *Modiola Fittoni.* Purbeck beds.
9. *Archæoniscus Brodiei* (M. Edw.). Purbeck. Vale of Wardour.
10. *Cidaris Purbeckensis* (Forbes). Middle Purbeck (Cinder bed).



PURBECK AND WEALDEN FOSSILS



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CRETACEOUS FOSSILS.

(*Neocomian.*)

PLATE L.

CRETACEOUS FOSSILS.

(Neocomian.)

1. *Exogyra sinuata* (Sow.). Upper Neocomian. Kent, Sussex, Speeton, etc.
2. *Perna mulleti* (Desh.). Upper Neocomian. Kent, Isle of Wight, etc.

2a. *Do.* Hinge-line showing vertical dentition.

3. *Pecten cinctus* (Sow.). Middle Neocomian. Lincolnshire.
4. *Crioceras* (*Ancyloceras*) *Duvalii* (Leveillé). Upper Neocomian. Speeton, Yorkshire.
5. *Ancyloceras gigas* (Sow.). Upper Neocomian. Isle of Wight, Sandgate, etc.
6. *Nautilus plicatus* (Fitton). Upper Neocomian. Kent, Isle of Wight, etc.
7. *Ammonites* (*Hoplites*) *noricus* (Schloth.). Lower Neocomian. Speeton.
8. *Ammonites* (*Hoplites*) *Deshayesii* (Leym). Upper Neocomian. Isle of Wight, etc.

(Plate L. fig. 1), *Perna mulleti* (Plate L. fig. 2), *Gervillia sublanceolata*, and *Ammonites Deshayesii* (Plate L. fig. 8).

NORTHERN DISTRICT.

The Lower Cretaceous of Lincolnshire and Yorkshire is wholly marine, and shows a palæontological relationship to the Cretaceous of the Baltic area; and many of the species of molluscs, though unknown in the South of England or in North France, are common in Northern Russia.

The deposits are mainly dark-coloured clays and shales which follow the Jurassic with no appearance of a stratigraphical break. Since they are marine and contain a different fauna, these beds cannot be correlated stage by stage with the deltaic series in the south of England.

The Speeton Clay, which is so well displayed in the neighbourhood of Speeton, north of Flamborough Head in Yorkshire, is the most important division of the northern Lower Cretaceous, and may be regarded as typical of the whole series of which it forms the major part. It contains a prolific molluscous fauna dominated by Belemnites and Ammonites; but in one thin band the characteristic sea-urchin *Echinospatagus cordiformis* is fairly common.

Palæontologically the series has been divided by Lamplugh into four Belemnite zones—

4. Zone of *Belemnites minimus* (base of Gault).
3. ,, ,, *brunsvicensis*.
2. ,, ,, *jaculum*.
1. ,, ,, *lateralis* (passage-bed).
0. Coprolite Bed.

The Coprolite Bed is a seam of phosphatic nodules about four inches thick, which appears to rest quite conformably on the Upper Kimmeridgian with *Belemnites Oweni*. It is not regarded as the uppermost portion of the Kimmeridgian. The lowest part of the Speeton clay is Purbeckian. The Portlandian is absent. The coprolitic [1] character of the bed might, however, be taken to indicate a short cessation of deposition before the deposition of the marine clays commenced.

Upper Cretaceous.

As a result of the great Cenomanian transgression of the sea the Upper Cretaceous was deposited over a wider and more uniform sea than the Lower Cretaceous; hence it extends far beyond the limits of that division. In some regions the overlap is so great that the Lower and Upper Cretaceous might very well be regarded as two distinct systems.

Lithologically the Upper Cretaceous is divided into three stages, namely an argillaceous stage at the base=the *Gault*; a sandy stage in the middle= the *Upper Greensand*; and a calcareous stage at the top=the *Chalk*.

In England, the Upper Cretaceous is well developed in the Southern, Middle, and Northern Districts; and in each district the various divisions exhibit a remarkable uniformity of character, except the chalk, which in the Northern District is thinner than in the South, and not argillaceous at its base.

[1] *Kopros*=dung, and *lithos*=a stone.

Upper Cretaceous	3. Chalk	Upper Chalk	—Senonian.
		Middle Chalk	—Turonian.
		Lower Chalk	Cenomanian.
	2. Upper Greensand,		Cenomanian.
	1. Gault, . .		Albian.

The Gault.—The Gault is dominated by the argillaceous facies of sediments. Lithologically it consists of stiff, dark blue, marine clay, in places sandy and marly, with lines of pyritic and phosphatic nodules. Its thickness varies from 100 to 300 feet, and in many places it overlaps the Lower Cretaceous.

The Gault contains many beautifully preserved fossils, large numbers of which may be seen at low tide at Copt Point, on the coast near Folkestone, where the Chalk rests directly on the Gault. Ammonites are plentiful, and among other molluscs are *Aporrhais*, *Pleurotoma*, *Cerithium*, *Fusus*, *Natica*, *Dentalium*, *Corbula*, *Pinna*, *Cucullœa*, *Mytilus*, *Ostrea*, *Pecten*, *Inoceramus*, *Cyprina*, and *Pholas*, the last seven being commonest in the higher beds.

A small Belemnite, *Belemnites minimus*, is very abundant and characteristic, as also are *Terebratula biplicata* (Plate LII. fig. 11), *Inoceramus salcatus*, *I. concentricus*, *Ammonites interruptus*, and *A. rostratus*, all of which are present in the contemporaneous *Red Chalk* of Yorkshire.

Upper Greensand.—This division is dominated by sandy beds, but there is no sharp line of demarcation between it and the Gault. The prevailing colour is dark green, due to the presence of glauconitic grains. In places where the glauconite has become oxidised, the sands assume a yellow, yellowish-brown, or red colour.

Nearly half the molluscs of the Gault pass up into the Upper Greensand, which is now known to be the local equivalent of different horizons of the Chalk series.

Palæontologically the Upper Greensand is divided into two well-marked zones—

2. Zone of *Pecten asper*.
1. ,, *Ammonites rostratus*.

The Lower Zone contains, among other characteristic species, *Venus submersa*, *Arca glabra*, *Pecten quinquecostatus* (Plate LII. fig. 9), *Ammonites rostratus*, and *Hamites alternatus*; and the Upper Zone, *Terebratula biplicata*, *Pecten asper* and *Ammonites varians*.

In the Central District the Gault (Albian) and Upper Greensand possess the same physical characteristics and fossils as in the south of England, but going northward the sandy beds comprising the Upper Greensand are gradually replaced by clay, and in Bedfordshire finally disappear, so that north of this the Upper Greensand is no longer recognisable as a separate member of the Upper Cretaceous.

In the Northern District the Albian (Gault + Upper Greensand), now mainly represented by clay, thins out and gradually passes into a bed of red chalk which is well seen in the sea-cliffs of Hunstanton in Norfolk, where it is about three feet thick and contains the characteristic fossils of the Albian of the south of England.

Going northwards, the *Red Chalk* expands to ten or twelve feet, and in the neighbourhood of Speeton still further thickens and passes into beds of reddish-coloured marls and clays with irregular seams of red chalky marl.

The Chalk.—The Chalk is the most conspicuous of the Upper Mesozoic formations of North-West Europe. It is a soft earthy limestone mainly composed of the shells of foraminifera among which the genus *Globigerina*

predominates. At its base it becomes argillaceous, forming what is called *Chalk Marl*; and in some places it contains grains of glauconite.

Nodules of flint arranged in lines parallel to the original planes of deposition are scattered throughout the Chalk and are particularly prevalent in the *Upper Chalk*, which has for that reason been called *White Chalk with flints*. The *Lower Chalk* has been called the *White Chalk without flints*; but this basis of subdivision is not satisfactory, since the lower part of the Chalk frequently contains flints, and the upper part in some cases does not.

The Chalk Series is divided, on palæontological grounds, into three distinct stages, namely—

Chalk Series	Upper Chalk —Senonian.
	Middle Chalk—Turonian.
	Lower Chalk —Cenomanian.

Conditions of Deposition.—The Chalk is mainly composed of foraminiferal ooze, a kind of deposit which at the present day is always associated with deep oceanic waters. The geographical position of the Chalk of North-West Europe and North America, and the presence in it of sandy beds as well as a mixed molluscous fauna, including *Terebratulina*, *Rhynchonella*, *Pecten*, *Ammonites*, *Belemnitella*, and other genera, besides numerous sea-urchins and the crinoid *Marsupites*, would seem to indicate that the original calcareous sediments were laid down in clear but comparatively shallow waters such as now exist in the fiords of Norway and New Zealand.

The palæontological zones into which the Upper Cretaceous is divided are as follows:—

Upper Chalk	Zone of *Ostrea lunata*	Senonian.
	,, *Belemnitella mucronata*	
	,, *Actinocamax quadratus*	
	,, *Marsupites testudinarius*	
	,, *Micraster cor-anguinum*	
	,, ,, *cor-testudinarium*	
Middle Chalk	,, *Holaster planus*	Turonian.
	,, *Terebratulina lata*	
	,, *Rhynchonella Cuvieri*	
Lower Chalk	,, *Holaster subglobosus*	Cenomanian.
	,, *Ammonites varians*	
	,, *Pecten asper*	
Upper Greensand and Gault	,, *Ammonites rostratus*	Albian.
	,, ,, *lautus*	
	,, ,, *interruptus*	
	,, ,, *mammillatus*	

Climate.—The character of the land vegetation, reptilians, and marine mollusca would seem to indicate the prevalence of a semi-tropical to tropical climate and warm seas such as may now be found on the coasts of West Africa and Malaysia.

Scotland.

Cretaceous rocks occur in the Isle of Mull and on the margin of the neighbouring Morvern Peninsula. In these areas they owe their preservation to the covering of Tertiary basalts. The rocks belong to the Upper Cretaceous, and contain evidence of deposition on the shores of an estuary, or landlocked inlet of the sea.

Ireland.

Upper Cretaceous rocks appear round the borders of the Antrim plateau, and, as in West Scotland, owe their preservation to the covering plateau of basalts. They rest unconformably on Jurassic and older rocks, and bear witness to the widespread character of the great Cenomanian transgression.

Cretaceous of other Countries.

North France and Belgium.—The Cretaceous rocks of North France and Belgium are lithologically and palæontologically closely related to the Cretaceous of England, of which they are obviously the eastern extension laid down in a prolongation of the same sea.

The subdivisions recognised in France are—

Upper Cretaceous	9. Danian.
	8. Senonian.
	7. Turonian.
	6. Cenomanian.
Lower Cretaceous	5. Albian.
	4. Aptian.
	3. Barrêmian.
	2. Hauterivian.
	1. Valonginian.

The characteristic fossils of the corresponding English subdivisions are well represented in these stages.

Danian.—The Danian stage, so called from its typical development in East Denmark, seems to bridge the hiatus between the Senonian and the Montian (or lowermost Eocene) as developed in France. Its fauna, while mainly Cretaceous, contains many Cainozoic types.

Rocks of Danian age are well developed in the northern Cretaceous basin of Western Europe, where they consist chiefly of grey and yellowish-coloured chalk and chalky marls that usually rest on an eroded surface of the underlying Senonian chalk.

The so-called Pisolitic (really Lithothamnium) Limestone of French geologists occurs in isolated patches in the neighbourhood of Paris, and in the department of Oise and Marne, and rests unconformably in different parts of the Cretaceous series, forming *passage-beds* into the Tertiary formations. The lowermost of these deposits is a hard, coarse-grained limestone containing the characteristic species *Neithea quadricostata* and *Nautilus herbertinus.* The concretionary limestone of the upper division, representing a transition to the *Montian* sub-stage of the Tertiary system, has yielded among many fossil molluscs, *Pleurotoma penultima, Neithea quadricostata. Lima texta,* and the very characteristic Danian cephalopod, *Nautilus danicus.*

The *Maestricht Chalk* in Holland contains a rich fauna, which includes *Nautilus danicus, Baculites Faujasi* (Plate LI. fig. 14), *Belemnitella mucronata* (Plate LI. fig. 13), *Ostrea vesicularis* (Plate LII. fig. 7), *Cidaris Faujasi, Micraster tercensis, Hippurites, Spherulites, Prœradiolites,* many fish remains, and numerous bones of *Mosasaurus camperi,* the last of the great Cretaceous mosasaurids. Usually the Maestricht Chalk is regarded as Upper Senonian.

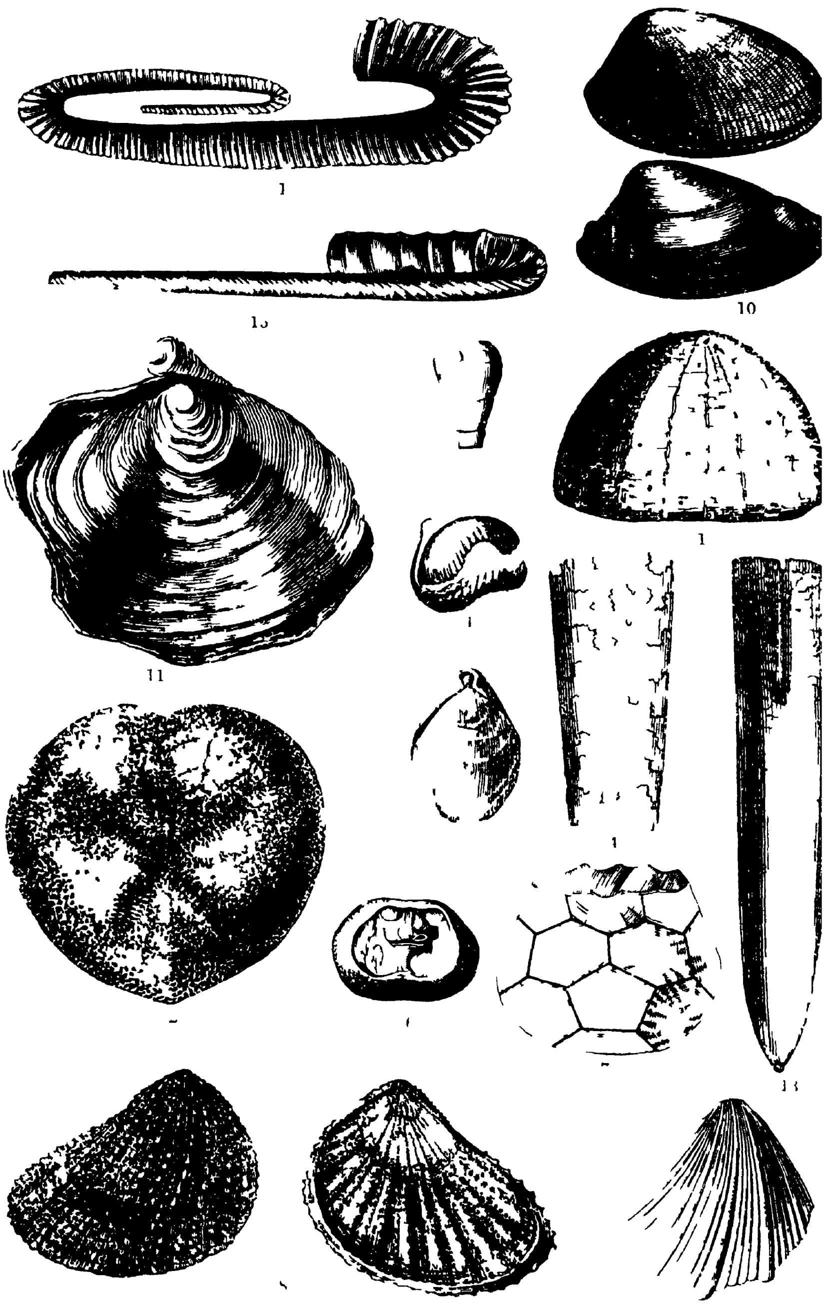
The *Faxoe Chalk,* which forms the lower division of the Danian in East

PLATE LI.

CRETACEOUS FOSSILS.

(Various.)

1. *Ananchytes ovata* (Leske). Upper Chalk. Kent, Sussex, Surrey, Isle of Wight, Wilts, etc
2. *Micraster cor-anguinum* (Leske). Upper Chalk. Kent, Surrey, Sussex, Norfolk. Wilts, etc.
3. *Bourgueticrinus ellipticus* (Miller). Portion of stem and calyx. Upper Chalk. Norfolk, Kent.
4. *Rhynchonella octoplicata* (Sow.). Upper Chalk. Norfolk, Kent, Sussex, Wilts.
5. *Terebratulina striata* (Wahl.). Upper Chalk.
6. *Crania parisiensis* (Defr.). Upper Chalk. Kent, Norfolk, Brighton, etc.
7. *Marsupites ornatus* (Miller). Upper Chalk. Lewes, Basingstoke, Blandford, Brighton.
8. *Plicatula placunea* (Lam.). Upper Neocomian.
9. *Pecten (Janira) quinquecostatus* (Sow.). Lower Chalk, Upper Greensand, Gault, Neocomian.
10. *Nucula pectinata* (Sow.). Gault. Folkestone, Cambridge, etc. Shell (above) and cast (below).
11. *Exogyra sinuata* (Sow.). Neocomian. Kent, Sussex.
12. *Hamites* sp. Gault. Folkestone.
13. *Belemnitella mucronata* (Schloth.). Upper Chalk. Norfolk, Kent, Sussex, Cambridge.
14. *Baculites anceps* (Lam.). Upper Chalk. Norwich, Sussex, etc.
15. *Ptychoceras adpressum* (Sow.). Gault. Folkestone.



Cretaceous Fossils.

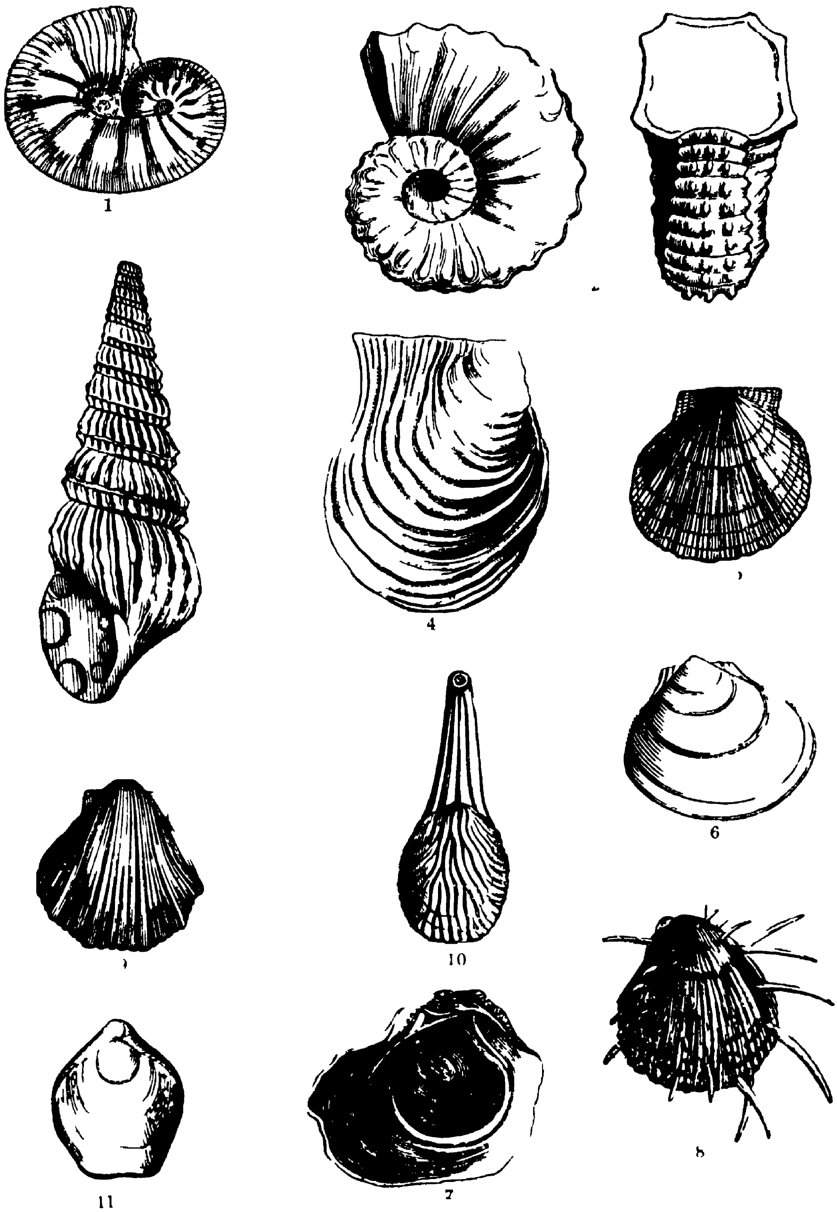
(Various.)

PLATE LII.

CRETACEOUS FOSSILS.

(Upper Greensand and Chalk.)

1. *Scaphites æqualis* (Sow.). Lower Chalk, Chalk Marl. Lewes, Evershot, Chardstock.
2. *Ammonites (Acanthoceras) Rhotomagensis* (Brongn.). Lower Chalk. Sussex, Hampshire, etc.
3. *Turrilites costatus* (Lam.). Lower Chalk. Hamsey, Folkestone, Compton, Norwich.
4. *Inoceramus Cuvieri* (Sow.). Upper and Lower Chalk. Lewes, Royston, Petersfield, etc.
5. *Pecten Beaveri* (Sow.). Lower Chalk. Kent, Wilts, Sussex, Norfolk, etc.
6. *Lima Hoperi* (Sow.). Upper Chalk. Norwich, Lewes, Surrey, Kent, etc.
7. *Gryphæa vesicularis* (Lam.). Upper Chalk. Kent, Sussex, Norfolk.
8. *Spondylus spinosus* (Sow.). Lower and Upper Chalk. Norfolk, Sussex, Kent.
9. *Pecten (Janira) quinquecostatus* (Sow.). Lower Chalk, Gault, and Neocomian—*passim.*
10. *Terebrirostra lyra* (Sow.). Chloritic Sand and Upper Greensand. Warminster.
11. *Terebratula biplicata* (Brocchi). Upper Greensand (Cambridge Greensand). Cambridge, Warminster, etc.



Cretaceous Fossils.

(Upper Greensand and Chalk.)

Denmark, is a hard yellow limestone full of bryozoa, with *Nautilus danicus* and numerous echinoderms, the latter including the genera *Holaster*, *Temnocidaris*, and *Dorocidaris*. The *Saltholmskalk*, or upper division, which is a chalk with flints, has been proved by boring to occupy a wide tract around Copenhagen under the glacial drift. It contains an abundant fauna in which *Nautilus danicus*, *Baculites Faujasi*, *Belemnitella mucronata*, *Ostrea vesicularis*, and *Terebratula carnea* are conspicuous. Similar strata and fossils occur in the south of Sweden.

The Danian is also strongly developed in the south of France, where it is represented by marly, chloritic, and compact limestones over 600 feet thick, with an abundant fauna, which includes such distinctive forms as *Nautilus danicus* and *Micraster tercensis*.

The presence of *Hippurites* of a very moderate size in the Danian of Denmark and Sweden indicates the prevalence of a climate in the Baltic zone less warm than in the Mediterranean region.

The Danian stage appears to have no representative in England. The uppermost Cretaceous beds which appear on the Norfolk coast, at Trimmingham, near Cromer, are regarded as uppermost Senonian.

A very complete succession of Cretaceous strata occurs in Persia, India, Japan, and United States, including representatives of the Senonian and lower Danian.

The highest division of the Upper Cretaceous on the east coast of Southern India, from Pondicherri to Trichinopoli, contains the well-known Danian fossil *Nautilus danicus*, which has also been identified in the Upper Cretaceous of Persia.

The great freshwater Laramic formation, which forms the chief Lignitic series of North Utah and Wyoming, reaches from the Senonian to the Danian, and is separated by a strong unconformity from the lowermost Eocene. It is believed by some writers to form a *passage-bed* leading up to the Tertiary formations.

No strata of Danian age have been recognised in Australia.

Wherever Cretaceous and Eocene formations are present, the palæontological break is always sharply defined, even in places where the stratigraphical discordance is absurdly insignificant.

It should be noted that in Europe *Ammonites* and *Belemnites* disappear before the Danian stage is reached.

Germany.—The Cretaceous rocks of Germany and the Baltic area were laid down in prolongations of the same sea as the English Cretaceous of the Northern District, and consequently present the same palæontological succession, and to some extent the same lithological features.

In Germany, the Cretaceous System is well developed in Saxony, Hanover, and Westphalia. It exhibits a chalky facies in the west, and a sandstone facies in the east. The latter, known as the Ouadersandstein, forms the pillaresque walls of the gorge of the Elbe near Dresden, and occupies a large area in northern Bohemia.

The Upper Cretaceous terrestrial beds of Aix-la-Chapelle and other places contain an abundant flora, comprising many monocotyledons and dicotyledons.

Russia.—Cretaceous rocks cover an extensive tract in the valleys of the Dniester, Don, and Volga, and generally bear a relationship to the Cretaceous of North-West Europe.

Mediterranean Basin.—There is a great development of the southern facies of the Cretaceous in the regions abutting on the Mediterranean Basin,

notably in Portugal, Spain, South France, Sicily, Italy, Switzerland, the Carpathians, Greece, Asia Minor, and Syria. Also in Morocco, Algiers, Tunis, and Egypt they cover a vast area which extends almost to the southern limits of the Sahara desert.

Palæontologically, the Mediterranean facies is characterised by the extraordinary prevalence of the peculiar Lamellibranch *Hippurites* on the Upper Cretaceous, which is a cone-shaped shell provided with a lid. The *Hippurites* lived in banks in shallow water, and grew in such numbers as to compose thick beds of limestone. Ammonites attain a large size and belong, in part, to the sub-genera with free-whorled, hooked, and highly ornamented shells. Among these Ammonites, *Buchiceras* is widely spread and characteristic.

A remarkable and interesting feature of the Cretaceous as developed in the Alps is a vast pile of sandstones and shales commonly known to Continental geologists as the *Flysch* or *Vienna Sandstone*. This rock formation extends from south-west Switzerland through the northern Alps to Vienna. It is conspicuously unfossiliferous, with perhaps the exception of some fucoid-like markings that afford no evidence of its age. The lower portions of this great accumulation of fluviatile deposits are known to be Cretaceous from the presence of fragments of *Inoceramus*. The upper portion may be Eocene or even later date, but this is not certain.

The lithological character of this mass of unfossiliferous rocks is so distinctive that the name *Flysch* is now recognised as a descriptive term for all such accumulations of similar unfossiliferous strata, regardless of their age.

India.—The Cretaceous System is represented in India by a great assemblage of marine and fluviatile deposits occurring both in the Peninsular area and the Himalayan. The rocks are largely limestones and shales, but sandstones and shales of the Flysch facies are extensively developed in both regions.

All the stages of the Cretaceous have been recognised in the coastal region by their faunas, which show a remarkable relationship to those of North-West Europe.

Upper Cretaceous	Danian, with *Nautilus danicus*.
	Senonian.
	Turonian.
	Cenomanian. Not known in Himalayan region.
	Albian. Absent in Himalayan region.
Lower Cretaceous	ian.
	Neocomian.

The effects of the Cenomanian transgression are particularly evident in the Peninsular region, where the Upper Cretaceous covers large tracts that in many places extend inland far beyond the limits of the Lower Cretaceous.

A notable feature of the Upper Cretaceous of India is the evidence of volcanic outbursts on a titanic scale and, so far as is known, unparalleled in the history of the globe. Towards the close of this period a succession of floods of lavas overwhelmed the greater portion of the Peninsular area, in places attaining a depth of 10,000 feet. The lavas are mainly augite basalts and dolerites that constitute what is commonly known as the *Deccan Trap*.

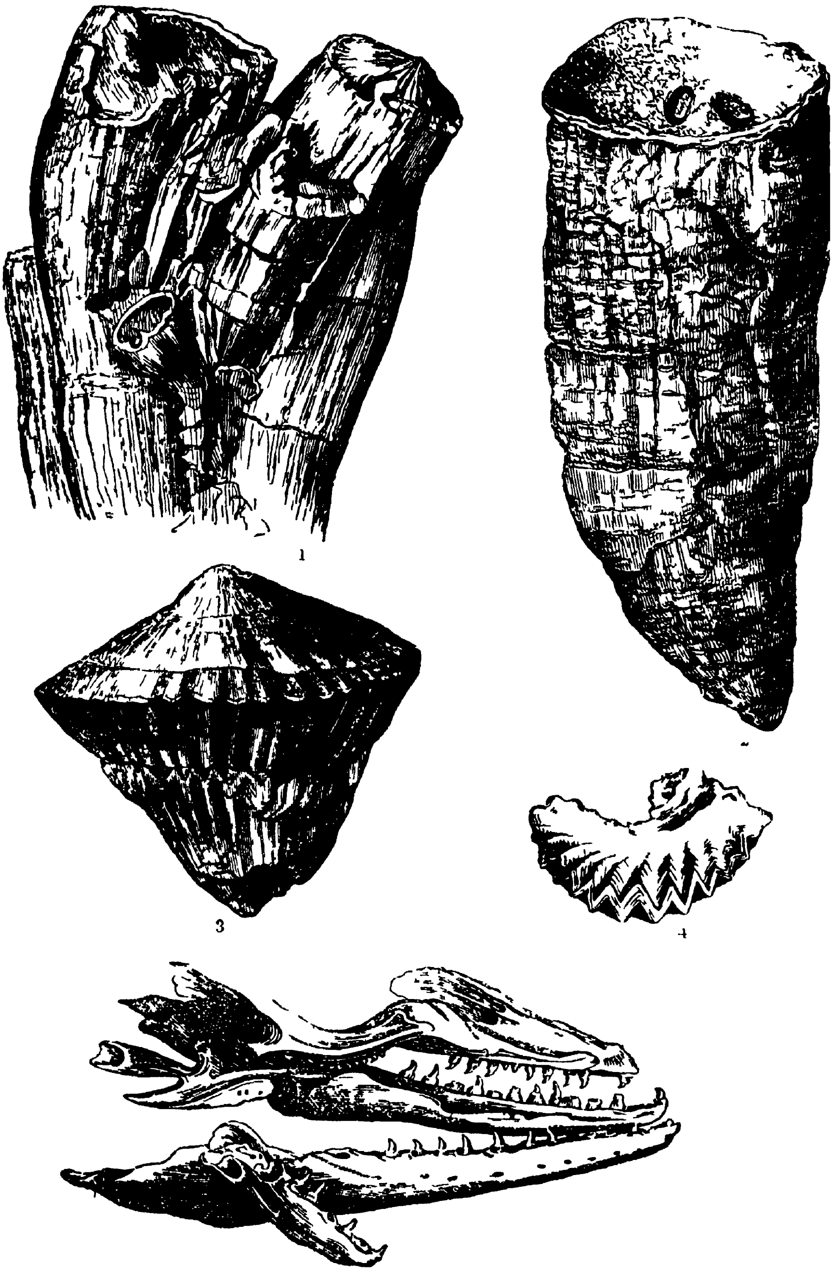
Concurrent with these outbursts, violent volcanic eruptions also took place in the Himalayan area, the ejected material consisting mainly of tuffs supposed to be submarine, rhyolitic, andesitic, and basaltic lavas, all of which are intruded by later gabbros and chrome-bearing serpentines.

North America.—The Cretaceous rocks of North America fall into two

PLATE LIII

CRETACEOUS FOSSILS.

1. *Hippurites organisans* (Mtf.). Chalk of France.
2. *Hippurites bioculatus* (Lam.). .. ..
3. *Sphærulites ventricosus*. .. ..
4. *Ostrea carinata* (Lam.). Chalk, Marl, etc.
5. Head (Upper and Lower Jaw) of *Mosasaurus Camperi* v. Mey. From the Upper Chalk of Maestricht.



CRETACEOUS FOSSILS

(*Chalk*)

great formations that differ greatly in lithological character, fauna, and geographical distribution, this last arising from the Cenomanian transgression, the effects of which are perhaps more marked in North America than in any other continent.

After the deposition of the Early Cretaceous deposits there was a widespread upward movement, that progressed till these early beds became partially eroded. Towards the end of the Middle Cretaceous there began a downward movement, and in the Late Cretaceous the sea overlapped the Early Cretaceous strata. The transgression that now took place is one of the notable events in the history of the American continent. On the Atlantic and Gulf borders the sea spread southward to Mexico and Texas, and northward over the Great Plains to the Arctic Ocean, forming a great Mediterranean Sea four hundred miles wide. At this time two-thirds of North America, as we now know it, was covered by the sea.

Before the close of the Cretaceous, diastrophic uplift began, and as a result the sea retreated southward, so that in the Gulf area the borders of the continent were extended even beyond the present limits.

In North America, as a consequence of the transgression, there is the same faunal contrast between the north and south Cretaceous facies as in Europe. In Mexico, Texas, and California, the southern or equatorial facies is characterised by the presence of *Hippurites*, *Nerinæa*, and the Ammonite *Buchiceras*, all found in Southern Europe, as also in Syria, Persia, and India.

The northern facies with white chalk is typically developed in Colorado.

The Lower Cretaceous, or *Comanchean System*, as it is sometimes called by American geologists, extends as a narrow strip along the old Atlantic border from New Jersey southward to South Carolina, and through Virginia, Georgia, Alabama, and Tennessee. From the Mississippi Basin it sweeps round the Mexican Gulf, whence it passes northward to Texas and southward to Mexico. It is also typically developed on the Pacific side of the continent, notably in the Sacramento Valley and coastal ranges of California, Oregon, and Washington.

The Upper Cretaceous (*Cretaceous System* of North American geologists) follows the Lower Cretaceous round the old Atlantic border and Mexican fringe, whence it spreads out over Texas. Here it overlaps the Lower Cretaceous and extends northward as a broad belt through the Great Basin to British Columbia and Alaska.

In this region the Cenomanian transgression amounted to over two thousand miles, and curiously enough it followed a line of depression running parallel with the axis or fulcrum along which the tilting of the continent took place in the Middle Mesozoic.

The Lower Cretaceous Series consists mainly of sandy, clayey, and calcareous deposits of marine origin; and the Upper Cretaceous mainly of estuarine, lacustrine, and terrestrial sediments.

Lower Cretaceous.—On the Atlantic border, this great group of beds is known as the *Potomac Series*, and in the Mexican Gulf region as the *Tuscaloosa Series*. These two series are in part, or perhaps mainly, contemporaneous.

The Potomac Series is chiefly composed of estuarine and terrestrial deposits, and the Tuscaloosa Series of marine sediments, among which chalk and compact limestones are well represented.

In Mexico the Lower Cretaceous attains a vast thickness, which is variously estimated at from 10,000 to 20,000 feet; and in California the Shastan Series (=the Comanchean) has an estimated maximum thickness of 26,000 feet.

Upper Cretaceous.—The subdivisions of this series in Montana and Colorado, where we have its greatest development, are as follows:—

Upper Cretaceous	4. Laramie.—Mainly brackish waters, lacustrine and terrestrial, with seams of lignite. 3. Montana.—Lower division, marine; upper, estuarine. 2. Colorado.—Lower portion mostly shales; upper portion, chalk. 1. Dakota.—Mainly continental and estuarine, with coal-seams.

The Upper Cretaceous rocks at one time stretched in a continuous sheet from the Gulf of Mexico to Alaska, and were laid down in an inland basin on the shores of which coal vegetation grew luxuriantly. The sea had free access to the basin till the middle of the Montana stage, when a general uplift introduced brackish-water conditions, and eventually cut off all communication with the sea. It was in this great land-locked basin that the famous Laramie lignitic formation was laid down. This inland basin was 2000 miles long and 500 miles wide.

The Laramie Series follows the Montana Series conformably, and is overlain unconformably by the Eocene. It is the principal coal-bearing formation of the Western States, altogether covering an area of about 100,000 square miles. The coal belongs to the lignitic variety, except in some parts of Colorado, where it has been altered to anthracite by local igneous intrusions.

At the close of the Cretaceous there was a sudden and violent revival of volcanic activity in many parts of North America; and the outbursts were particularly intense in the Crazy Mountain area of Montana.

Fauna and Flora.—The Cretaceous Systems of North America contain prolific and varied faunas and floras, among which the northern and southern facies of Europe are typically developed.

The reptilian fauna is specially notable for the number and variety of its dinosaurs, pterodactyls, crocodiles, turtles, and plesiosaurs.

The marine molluscous fauna is mainly dominated by Ammonites and Belemnites, many of which, as in Europe and Asia, possess a zonal importance. All the characteristic genera of Lamellibranchs, Gasteropods, and sea-urchins that distinguish the European Cretaceous are well represented in North America.

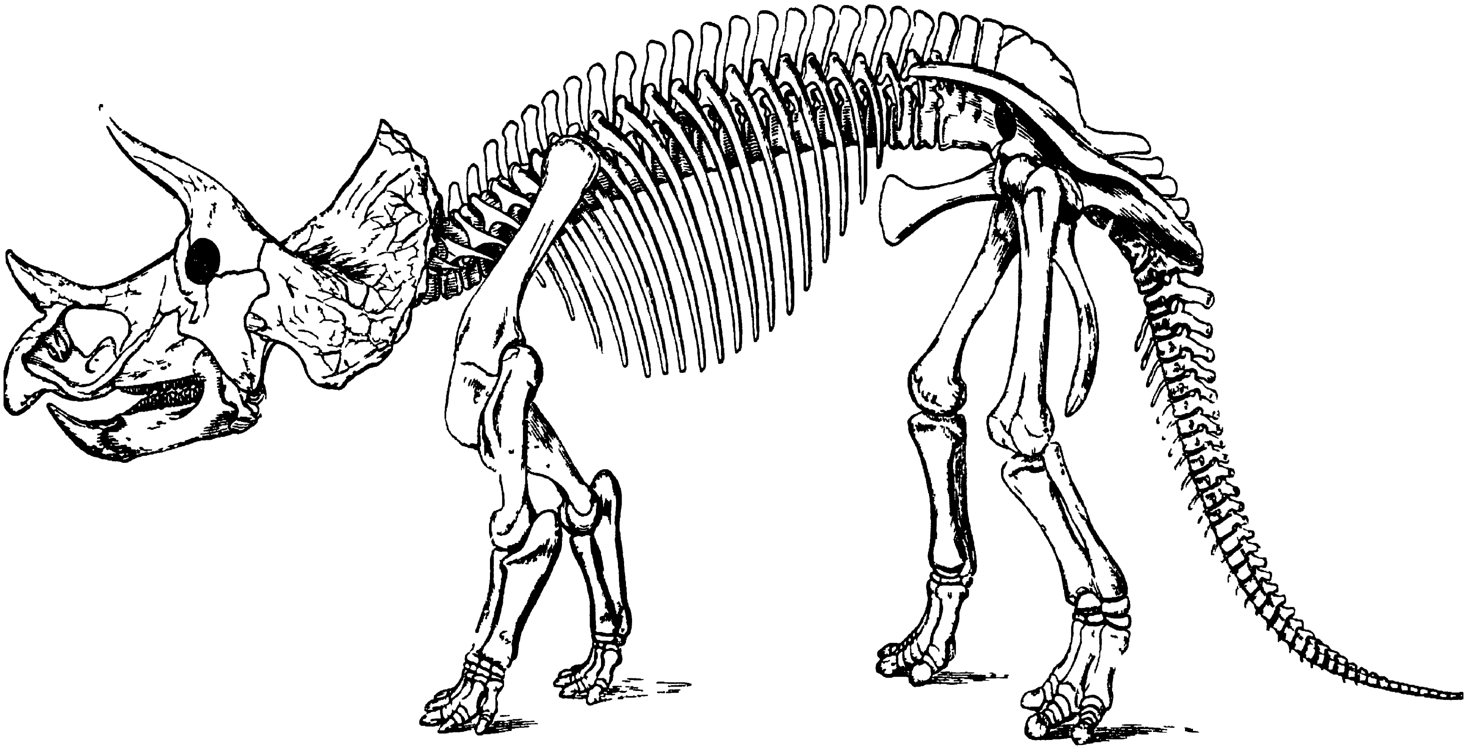
The land flora of the Laramie Lignitic Series contains a large assemblage of forest trees, including representatives of the oak, willow, beech, plane, poplar, maple, hickory, fig, and sassafras, with many ferns, cycads, and conifers.

South America.—Cretaceous rocks are widely distributed throughout Brazil, Peru, Chile, and Patagonia.

In Brazil the Upper Cretaceous division extends far beyond the domain of the Lower Cretaceous, and consists mainly of marine sediments. Rocks of Senonian appear in the neighbourhood of Concepcion, especially on the island Oudaiguinai. The fauna of the Upper Senonian of Patagonia, as well as that of Oudaiguinai, shows remarkable relations to that of New Zealand.

Antarctic Continent.—In the islands, Snow Hill and Seymour Island, on the eastern side of Graham's Land, there occur sandstones with a rich fauna of Upper Senonian age. The molluscs are related to fauna of the same age in Patagonia, Chile, and New Zealand.

North Africa.—The Lower Cretaceous rocks of North Africa are mostly confined to the region fringing the south-west borders of the Mediterranean basin, including the Atlas Mountains. But as a result of the Cenomanian



RESTORATION OF TRICERATOPS PRORSUS (CRETACEOUS, WYOMING. (Marsh, U.S. Geol. Survey.)

transgression, the Upper Cretaceous Sea overspread all the low-lying areas of North Africa, thereby covering the greater portion of what are now the Saharan, Libyan, and Nubian deserts. Altogether the sea invaded an area amounting to many hundred thousand square miles.

The best-known and perhaps most widespread member of the Upper Cretaceous in North-East Africa is the *Nubian Sandstone*, a reddish-brown or grey sandstone which contains only silicified wood and in many places bears a curious resemblance to the *Desert Sandstone* of Queensland. It belongs to different stages of the Upper Cretaceous. In the Libyan Desert the Nubian Sandstone is overlain by white chalk which, among other fossils, contains the sea-urchin *Ananchytes ovata*, a characteristic form of the Senonian of North Germany.[1]

From Egypt the Nubian Sandstone passes into Syria and Arabia.[2] In Syria Upper Cretaceous rocks with *Hippurites* are very largely developed. The famous fish-bearing rocks in Lebanon are in part Cenomanian (Hakel), and in part Senonian (Satel Alma).

South Africa.—The Cretaceous rocks of South Africa are divided into two groups, which occupy separate geographical areas. Both are shallow-water marine deposits, and each group begins with a coarse basal conglomerate.

The two groups are the *Uitenhage Series* and the *Pondoland Series*. The latter occupies two narrow strips along the coast; while the former is mainly displayed in a disturbed and folded zone lying between the Karoo and the coast.

The Uitenhage Series consists mainly of sandstones, clays, shales, and limestones, with conglomerates at the base. It is divided into three stages—

$$\text{Lower Cretaceous}\left\{\begin{array}{l}\text{3. Sunday's River Beds}\\ \text{2. Wood Beds}\\ \text{1. Enon Beds}\end{array}\right\}\text{Mainly Neocomian.}$$

The clays of the *Enon Beds* have yielded the remains of dinosaurs; and the Wood Beds contain an interesting series of fossil plants comprising many ferns, cycads, and conifers. Among the ferns are such well-known genera as *Tæniopteris*, *Sphenopteris*, and *Cladophlebis*. Some of the beds are crowded with the broad fronds of the cycad *Zamites*, of which four species have been identified, including *Z. recta* and *Z. africana*. The conifers are represented by *Araucarites*, *Taxites*, *Conites*, and others.

Intercalated with the *Wood Beds*, there are two or more bands of marine deposits in which the molluscs *Ostrea*, *Psammobia*, *Pecten*, and *Turbo* have been found. In the fossil wood found in this formation there have also been discovered many examples of the small boring mollusc *Actæonina atherstonei*.

The *Sunday's River Beds* are shallow-water or estuarine, and contain a rich molluscous fauna which consists mainly of Lamellibranchs, Gasteropods, and Cephalopods. The Lamellibranchs include such littoral shells as *Astarte*, *Avicula*, *Cardita*, *Cucullæa*, *Exogyra*, *Gervillia*, *Lima*, *Pecten*, *Perna*, *Pinna*, *Mytilus*, *Modiola*, and *Trigonia*; the Gasteropods, *Natica*, *Patella*, *Trochus*, and *Turbo*; and the Cephalopods, *Baculites*, *Crioceras*, *Hamites*, and *Belemnites*.

The Pondoland Series occurs in two strips, the Umzamba and the Embotyi. The Umzamba, which is the more important, lies on the coast near the Natal boundary. It consists mainly of alternating bands of shelly limestone and hard marly clays of marine origin, with a large number of fossil molluscs, including

[1] W. F. Hume, *Geol. of Peninsula of Sinai*, 1906, p. 152; Max Blanckenhorn, "Ägypten" (*Handbuch der regionalen Geologie*, vii. 9), p. 44 (1921).

[2] Professor E. Hull, *Geol. of Arabia, Palestine, etc.*, 1886, p. 54; Max Blanckenhorn, "Syrien, Arabien, und Mesopotamien" (*Handbuch der regionalen Geologie*, v. 4), p. 17 (1914).

Cephalopods, which show a singular relationship to those of the Upper Senonian of Northern India, Japan, Vancouver Island, and Chile.

Australasia.—Cretaceous rocks occupy an enormous area in the Northern Territory, Queensland, and Western New South Wales. They are divided into two series, namely—

Upper Cretaceous (2)—Desert Sandstone.
Lower Cretaceous (1)—Rolling Downs Series.

The *Rolling Downs Series* consists mainly of marine clays which follow the Jurassic rocks quite conformably. It is mainly developed in Queensland, where it occupies or underlies an area of 500,000 square miles. The clays of this widespread formation constitute an impervious covering, and thereby imprison the fresh water contained in the underlying sandstones. The water rises freely to the surface when tapped by bore-holes. The economic importance of the Rolling Downs formation to the dry interior of Queensland is almost incalculable.

The *Desert Sandstone* consists of rusty-brown, gritty sandstones which are frequently current-bedded. It mostly occurs as isolated patches and outliers which form hills, ranges, and plateaux scattered throughout Queensland and Western New South Wales. Its present distribution shows conclusively that it was at one time a continuous sheet which occupied an area exceeding 500,000 square miles. This great formation is quite undisturbed, and rests unconformably on the Lower Cretaceous and on older rocks. We now have evidence that the perplexing Cenomanian transgression of the sea was world-wide and probably contemporaneous in both hemispheres.

The Desert Sandstone was laid down partly in a shallow sea bordering a great continent, and partly on the neighbouring low-lying desert lands. Near the bottom of the series on the present coast-line it contains intercalated marine beds from which a few molluscs have been obtained, including *Rhynchonella croydonensis*, *Leda elongata*, *Avicula alata*, and casts of Belemnites. The same beds contain the sea-urchin *Micraster sweeti*. In the Desert Sandstone in Western New South Wales there have been found the remains of the reptilian *Cimoliasaurus*; and in Central Queensland, broken plants and silicified trees in abundance. At Cooktown it contains coal-seams and silicified trees, and in the Clayton River district many leaf impressions.

The surface of the Desert Sandstone is frequently covered with a thin enamel or glaze of silica deposited by water. The siliceous cement stones of South New Zealand, and the surfaces of the mushroom-shaped deposits of siliceous sinter in the Hauraki Peninsula, are also covered with the same glaze, which is only formed on weathered surfaces.

Recent investigation would tend to show that the "Desert Sandstone" of Queensland does not form a distinct formation, but belongs to various systems between Tertiary and Permo-Carboniferous. The rocks of the White Cliffs opal-fields, long thought to be Upper Cretaceous, have now been found to contain a Lower Cretaceous fauna. It would appear as if the view which supposes the Desert Sandstone to be the representative of the Upper Cretaceous must be abandoned.

In New Zealand the Upper Cretaceous *Waiparan Series* consists of basal conglomerates and sandy beds with seams of coal and shales which contain the leaves of dicotyledonous plants. The Coal-Measures are followed by marly or shaly clays with calcareous concretions that frequently contain saurian remains. Then follow glauconitic greensands that are conformably overlain by chalky and hard limestones.

The reptilian remains found in the marly clays below the greensands include representatives of *Cimoliasaurus*, *Leiodon*, and *Platecarpus*. In the same beds are found the teeth of fishes, and a molluscan fauna including a few Cephalopods, and a great number of Gastropods and Lamellibranchs. Characteristic fossils are the Gastropod *Conchothyra parasitica* (M'Cloy, M. S.), and the Lamellibranchs *Trigonia Hanetiana* d'Orb. (occurring also in Chile), and *Tuoceramus Steinmanni* Wilck. (occurring also in Patagonia).

The succession of the Waiparan, of Upper Senonian age, and the overlying beds, that are Oamaruian (Miocene), as developed in North Canterbury—

Miocene (Oamaruian)	10. Greta beds. 9. Mount Brown beds. 8. Grey sandy clays and marls. 7. Weka Pass Stone (compact limestone).
Doubtful	6. Amuri limestone (chalky). 5. Glauconitic greensands.
Upper Senonian (Waiparan)	4. Marly clays, with concretions containing saurian remains. 3. Oyster-bed. 2. Quartz sands with brown coal. 1. Conglomerates.

The fauna of the Waiparan is characteristically Senonian and that of the Oamaruian, with 30 per cent. of living molluscan species, as distinctively Miocene. So far as known, the Glauconitic greensands, bed 5, is unfossiliferous; while the Amuri limestone is foraminiferal, and without molluscan remains. The appearance of stratigraphical conformity renders it difficult to define the position of the unconformity that must exist between the two systems. Recent discovery would appear to show that the break exists at the base of the Glauconitic greensands.

The Waiparan and Oamaruian are marginal to the main axial chain of the South Island.

Landscape and Physical Features.—The Cretaceous System, as seen in different lands, presents a great diversity of surface forms. The effects of denudation are found to vary with the character and succession of the rocks, the amount of tilting and faulting they have suffered, the height above the sea, the amount of rainfall, and general climatic conditions. Even the same rock-formation may assume different landscape forms in different regions.

The Chalk, in England, owing to its superior resisting power to the effects of subaerial denudation, wherever it occurs, forms striking features in the landscape. Thus the ranges of hills known as the North and South Downs, the Salisbury Plain, Chilterns, Lincolnshire Wolds, and Yorkshire Wolds, all owe their origin to the wearing away of the softer clays and sands and the survival of the chalk notwithstanding the wasting influence of the weather. In the same way the white cliffs of Dover, in South-East England, and of Flamborough Head on the north-east coast, owe their striking appearance to the resistance the chalk has offered to the assaults of the sea. Moreover, in the Isle of Wight, where the Cretaceous rocks are tilted at high angles, the chalk forms the central ridge which traverses the island, the surrounding softer rocks having been worn away by denudation.

In arid regions the effects of subaerial denudation are always strikingly uniform, and there is seldom seen the diversity of surface features which characterises temperate climates with an abundant rainfall. In temperate regions the rock-formations become dissected into a complex of ridges and

valleys, but in arid regions the general effect of the varying temperature and wind is to reduce the whole landscape to a monotonous level surface.

The Nubian Sandstone of North Africa forms long lines of even escarpment in the Libyan Desert; and the Desert Sandstone of North-East Australia frequently assumes the form of isolated flat-topped ridges bounded by steep walls, like the *mesas*[1] of Colorado; or pyramidal hills barred with the horizontal parallel lines of stratification, like the *buttes* of Wyoming.

Economic Minerals.—The Cretaceous System is notable for its valuable deposits of lignitic coal as found in the Laramie formation of the Western States of North America; and in the Waiparan Series of New Zealand. The chalk and other limestones of this system are also of great economic importance, in England, France, and elsewhere, as a source of lime for the manufacture of cement, and for agricultural purposes.

SUMMARY.

(1) The Mesozoic era is divided into three great systems, the *Triassic, Jurassic*, and *Cretaceous*. Generally speaking, the Triassic is the connecting-link with the Palæozoic era, and the Cretaceous with the Cainozoic.

(2) The Triassic as developed in England is continental, and shows a continuation of the conditions that prevailed in the Permian; but in Continental Europe there are two distinct facies of deposits, each occupying different geographical areas, and each characterised by a distinctive fauna. The two facies are the *Continental* and the *Marine*, the former typically developed in Central Germany and hence called the *German* facies; and the latter in the Alps, and hence known as the *Alpine* facies.

The deposits of the continental facies were laid down in inland basins or Mediterranean seas that after a time were cut off from all access to the sea. The extensive and valuable beds of rock-salt and gypsum associated with these deposits show that the climatic conditions of Central Europe and the corresponding latitudes in North America were not unlike those now prevailing in the arid regions of North Africa and Central Australia.

The Triassic deposits of the Alpine facies are marine, but the fauna is that of shallow water.

The Triassic System is specially distinguished by the appearance in it of the earliest known mammals which belong to a primitive type apparently related to the existing marsupials of Australia.

(3) The deposits and fossils of the Jurassic System show that the continents of that period were clothed with a rank vegetation, while the estuaries and seas swarmed with molluscs, fishes, and huge reptiles. Moreover, the forests teemed with insects, and the seashore was frequented by the peculiar toothed *Archæopteryx*, the earliest known bird.

The faunas of the Jurassic may be divided into geographical zones which encircle the globe in a direction parallel to the equator, and correspond to the biological zones that now exist in each hemisphere. It is presumed that this is the first evidence of the existence of climatic zones on the globe.

Ammonites were very numerous in the Jurassic seas; and the different species were so widely distributed throughout the globe and so limited in vertical range, that they are now useful in subdividing the various stages of the system into palæontological zones.

Cycads were so abundant and prominent among the land vegetation, and reptiles so numerous on the land, in the air, in the deltas and seas, that the

[1] Sp. *Mesa*=a table.

Jurassic has been sometimes called the *Age of Cycads*, and sometimes the *Age of Reptiles*. The latter name is sometimes applied to the whole Mesozoic era.

(4) The Cretaceous System everywhere falls into two great divisions, the Lower Cretaceous and the Upper Cretaceous. These two divisions are frequently associated in the same regions; but in all the continents, in both hemispheres, the Upper Cretaceous passes on to older rocks and stretches far beyond the limits of the Lower Cretaceous. This remarkable distribution of the Upper Cretaceous rocks was due to an invasion or transgression of the sea all over the globe, whereby all the low-lying lands and valleys fringing the continents were overwhelmed by the sea. The cause of this great inundation is unknown, but it may have been connected with the collapse of the Gondwana-Land continent, which we know existed in the Indian Ocean area up till the close of the Jurassic, and well into the Cretaceous period.

The marine life of the Cretaceous was not less abundant than that of the Jurassic; and while its general facies is distinctively Mesozoic, it is characterised by the appearance of many genera of marine molluscs which still live in our seas.

The Cretaceous flora is specially notable for the advent of angiosperms or flowering plants, including monocotyledons and dicotyledons, among which were representatives of most of the forest trees of the present day. Ferns, cycads, and conifers now grew side by side with the oak, beech, plane, willow, and other familiar trees; hence the general aspect of the forests must have resembled that of the existing forests of the warm temperate zones of the present day.

The Jurassic reptiles were still present in all parts of the globe, and particularly numerous in North America; but they disappeared before the close of the Cretaceous period, as also did the voracious Ammonites and Belemnites. The *Nautilus* survived the Cretaceous and still lives in warm, temperate, and tropical seas. Its persistence is possibly due to its habitat lying in the open deep seas, where it would be less affected by continental changes than the shallow-water Ammonites and Belemnites, the disappearance of which is, for the rest, difficult to explain.

Two distinct types of marine fauna are present in Europe and America, the northern and southern, the former or Central European characterised by soft foraminiferal chalk, and the latter or Equatorial by hard limestones frequently composed of the shells of the curious *Rudists*, which also spread eastward as far as Northern India and Tibet, and westward to Jamaica, Texas, and California, but appear to be unknown in the Southern Hemisphere. They are lamellibranchs with a very thick shell and of peculiar cone-shaped form.

CHAPTER XXXII.

CAINOZOIC ERA. TERTIARY SYSTEM.

Eocene and Oligocene.

THE Cainozoic is the youngest of the four grand divisions into which geological time is divided. It embraces the period from the end of the Cretaceous to the present time.

The palæontological break between the Lower Tertiary and the Chalk is the most striking and universal in the geological history of the globe. But the stratigraphical break is not, as might reasonably be expected, correspondingly great. On the contrary, it is seldom conspicuous, and in many places is scarcely visible, which renders the sudden change in the organic life of the Earth all the more remarkable and puzzling.

Great changes took place in the relative distribution of land and sea during the interval bridging the Chalk and Eocene; and there is abundant evidence that they were mainly due to a world-wide recession of the sea. But these changes were inconsiderable compared with those caused by the great Cenomanian transgression, which, as we know, was followed by no conspicuous acceleration in organic development. Nevertheless, we are probably not far from the truth when we assume that the remarkably sudden disappearance of old forms, and the advent of many new inhabitants in the interval between the Chalk and the Lower Tertiary period, were mainly due to physical and climatic changes; and though the stratigraphical break is apparently small, the time occupied in these changes may have covered a vast period of time.

The Cretaceo-Tertiary Hiatus.—During the long interval of subsidence and deposition that prevailed from the close of the Palæozoic to the late Cretaceous, the continents for the most part became worn down to a surface of low relief. Though perhaps enfeebled, denudation must have continued throughout the interval that bridges the Cretaceous and Eocene. And since denudation postulates the existence of streams, it is obvious that deltaic and marine sediments were deposited around all the continents during the Cretaceo-Eocene hiatus.

It is almost certain that the recession of the sea, that began at the close of the Cretaceous period, was relatively rapid and continued till the sea littoral became established at the edge of the continental shelf. The streams at this time cut deep, narrow channels across the wide coastal plains, and discharged the products of denudation into the abyssal depths lying seaward of the shelf. For this reason it is almost impossible that any portion of the marine sediments deposited during the Cretaceo-Eocene hiatus will ever be found.

Though the recession of the sea was probably measured by hundreds and not by thousands of feet, it exercised a profound influence on the existing fauna and flora. As the sea receded the marine molluscs retreated, and doubtless

continued to find a congenial environment till the edge of the shelf was reached. Here the real struggle for existence began. The weaker genera and species succumbed, and their place was taken by new species.

Where large rivers entered the sea, the transported detritus was piled up till wide-spreading deltas were formed on the littoral of the continental shelf. On the fan-like edges of these deltas, some of the older genera continued for a time the unequal struggle for existence.

It must be understood that the foregoing is only an attempt to explain the profound changes in the fauna, the problem being most puzzling.

During this period, the uplifted Cretaceous strata were subject to subaerial denudation, the extent of which was determined by the local geographical conditions. Where the continental surface relief was moderately high, the Cretaceous sediments were deeply eroded or entirely destroyed. But in the great basin areas, where the neighbouring relief was low, the surface of the Cretaceous strata suffered little; and in consequence, when the Eocene seas once more invaded these old Cretaceous basins, the Eocene sediments were deposited on the even, or almost even, surface of the Cretaceous strata. Hence though the biological break between the Cretaceous and Eocene is the most profound in the geological record, the physical unconformity in such areas is relatively insignificant. These are the conditions that existed in the great inland sea of the Gulf Region of North America, and on the southern borders of the Central Sea (Tethys) of Southern Europe.

Fauna and Flora.—The life of the Tertiary era is distinguished from the Cretaceous by the disappearance of many well-established Mesozoic genera and the sudden appearance of numerous highly organised forms of which we can find no trace of probable ancestors. Ammonites, Baculites, Hamites, Inocerami, Hippurites, and the remarkable reptilian Plesiosaurs, Ichthyosaurs, Pterodactyls, and monstrous Dinosaurs disappear as completely as if they had never existed, and their place is immediately filled by a congeries of highly developed placental mammals. The sudden appearance of the present-day mammals in the Miocene and Pliocene, and their mode of dispersal are still unsolved biological problems.

Many genera survived from the Mesozoic, but the organic hiatus is so complete that no single species higher in the scale than the primitive Foraminifera passed from the Cretaceous to the Tertiary.

Foraminifera are numerous throughout the whole of the Tertiary era and particularly abundant in the Middle and Upper Eocene; and the reef-building corals comparatively rare in the Chalk again become prominent in the Equatorial zones. The genera present in the later Tertiary deposits are mostly those now existing, and many of the species are identical with living forms. The Foraminifera, like other lowly forms of life, have been persistent in type, and show no evidence of fundamental modification or advance "from the Palæozoic period to the present time" (Carpenter). A number of the Cretaceous species appear to be inseparable from existing forms, while some living species are believed to date from even an earlier period.

Brachiopods show a marked decline, except perhaps in the Australian waters; but marine Lamellibranchs and Gasteropods are more numerous than ever. Ammonites have disappeared, but *Nautilus* and gigantic *Aturia* are still common. Crustaceans are now represented by numerous short-tailed decapods.

Among the vertebrates we have a great array of fishes, as well as snakes, crocodiles, and birds. Placental mammals, including ancestral forms of most of the living ungulates (hoofed-herbivores), appear in the Lower Tertiary for

the first time, and become prominent almost at once ; and associated with them we have representatives of the non-placental marsupials which are still the dominant endemic mammals of the Australian continent.

Before the close of the Tertiary era there appeared the anthropoid apes, and finally man

The flora is now dominated by the flowering Angiosperms, which are represented by a vast assemblage of monocotyledonous and dicotyledonous forms, which include the cactus, numerous palms, laurel, myrtle, magnolia, etc, comprising a luxuriant evergreen vegetation

Rocks.—The sedimentary rocks of the Cainozoic era in the Northern facies are mostly incoherent sands, clays, and pebbly beds with subordinate layers of marls and hard, shelly limestones; but in the Southern or Equatorial facies of the Lower Tertiary hard limestones, sandstones, and shales predominate

Marine and estuarine beds are largely represented, but deltaic, fluviatile, lacustrine, and desert deposits play an important *rôle* in all the Tertiary formations Towards the close of the era, glacial accumulations are conspicuous in many temperate latitudes

Generally speaking, the marine Tertiary deposits are marginal to the continental areas, and usually still lie horizontal, except where they have been involved in the structural folds of the great mountain chains, or locally disturbed by volcanic outbursts

Where the Tertiary systems are fully represented, they form a great succession of conformable strata, but where the succession is incomplete, there may be physical breaks of considerable magnitude In England, for example, where the Miocene is entirely absent, the Pliocene rests unconformably on the Eocene and older rocks

The volcanic activity which revived at the close of the Cretaceous after nearly an era of quiescence continued with periods of rest throughout the whole of the Cainozoic era There is much evidence in favour of the belief that all great crustal movements have been preceded or accompanied by violent displays of volcanic activity

Distribution.—The Tertiary systems are found in all parts of the globe, and in many regions there is a close geographical relationship between the Lower Tertiary formations and the Cretaceous It would appear that many Cretaceous areas of deposition after a lapse of time became areas of deposition in the Tertiary era, and in regions where the Cretaceous rocks suffered little deformation, the Tertiary strata frequently rest on them with no visible appearance of stratigraphical discordance

Rocks of Lower Tertiary age take part in the structure of the Alps, Apennines, Carpathians, Caucasus, Atlas, Himalayas, Andes, Rocky Mountains, Sierras, and many other great chains, all of which are therefore comparatively young When we pause to remember that the site of a gigantic mountain complex such as the Himalayan was a sea-floor so recently as the Middle Tertiary, we begin to catch a faint conception of the comparative rapidity of great earth-movements and of the titanic forces of which they are the visible expression.

The uplift of the Tertiary rocks in some regions is enormous In the Alps the Lower Tertiary Nummulitic Limestone occurs at a height of 11,000 feet above the sea, and in the Himalayas 17,000 feet

The Central Sea or Tethys.[1]—This great inland sea is the most striking and important geographical feature of the Mesozoic and Cainozoic, and the

[1] Tethys, the consort of Oceanus The name has been given by Suess.

sediments laid down on its floor and borders constitute nearly a complete geological history of the Old World in these eras.

This great sea was first outlined during the orogenic movements of the Carboniferous period as a deep corrugation or basin, running east and west in the latitudes of Southern Europe, and lying between the northern and southern continents, into which the Old World at this time became divided

On the floor of the seas occupying this great corrugation was laid down the Permo-Jurassic succession of conformable strata, so largely represented in the structure of the Alps and Himalayas But it was since the Trias (perhaps the Permian) that the Central Sea formed a continuous sea and completely severed the northern Russo-Siberian continent from the southern or Gondwana-Land continent

Before the close of the Cretaceous the Central Sea extended from the Atlantic eastward through Southern Europe to Further India and Burma It girdled half the globe with its length of 9000 miles, and its width varied from 1000 to 2500 miles

Gondwana-Land on the southern shores collapsed sometime about the Middle Cretaceous, perhaps contemporaneously with the great Cenomanian Transgression, and Central and Eastern Africa, a portion of Peninsular India, Malaysia, and Australia are all that now remain to mark its former extent. Of the surface forms of this great continent which covered so large a portion of the present Indian Ocean, or of the outlines of the Central Sea which washed its shores, we have little remaining evidence

On its north side the Central Sea was deeply indented with bays and great estuaries, into which the rivers draining the more permanent northern continent discharged their loads of detritus

These northern rivers, throughout the Cretaceous, Eocene, and Oligocene periods, reclaimed large deltaic areas on the fringe of the sea In the clearer waters beyond the reach of the detritus, marine sediments were laid down, largely composed of marine organisms, among which Nummulites predominated From their nature these marine deposits accumulated more slowly than the deltaic or Flysch detrital sediments, and hence did not attain the same great thickness

In this manner the Flysch and marine facies of deposits were formed contemporaneously in the same continuous sea, the deltaic as detached but extensive deposits on the northern coasts, the marine as continuous sheets that wrapped round the deltaic and extended seaward into the clear waters

That the waters of the Central Sea were clear and warm, except in the deltaic areas, up till the close of the Oligocene period is shown by the abundance of reef-building corals, sea-urchins, and the large size of the molluscs and Foraminifera

The Ca pian Sea is probably a remnant of the great Central Sea

The Baltic Sea.—At the close of the Carboniferous there came into existence a northern but smaller sea, running nearly parallel with the Central Sea This sea followed the Baltic depression, and extended eastward to the Urals, and although varying in width and extent at different periods, it continued an area of deposition up to the close of the Miocene The Baltic is a remnant of that ancient sea.

Up till the Trias it was separated from the Central Sea by a narrow ridge, but in the Rhætic this separation ceased, and was not renewed until the Cretaceous period From that time onward the separation continued to be more or less complete, and the dividing chain was broader than at any former time.

Origin of the Flysch[1] Facies of Deposits.—Deposits of the Flysch type are conspicuous in the structure of the Alps, Apennines, Carpathians, Caucasus, and mountain systems of Persia, Baluchistan, and Northern India.

They consist of alternating grey sandstones and gritty shales, or simply of shales alone, and are everywhere conspicuously unfossiliferous. Bands of fossiliferous calcareous strata are in a few places intersected with them, and in the adjacent areas they are frequently associated with massive beds of marine limestones.

The Flysch Series comprises a pile of strata which ranges in age from the Upper Cretaceous to the Oligocene. They are obviously composed of deltaic detritus that accumulated on the borders of the Central Sea at the mouths of the rivers draining the great northern continent. The detritus was not spread out as a continuous sheet along the shores of the Central Sea, but was piled up to a great thickness in the deltaic areas. At its outward fringes the material was in places intercalated with thin sheets of marine sediments.

In the clearer and deeper waters of the adjacent parts of the Central Sea there also accumulated, contemporaneously with the deltaic sediments, the thick deposits of calcareous sediments, which now form the massive beds of Nummulitic Limestone so conspicuous in the Alps, Carpathians, Baluchistan, and Himalayas.

The character of the sediments composing the Flysch Series, and the absence of organic remains, would tend to show that there was a considerable rainfall all over the northern continent, attended with rapid denudation of the land, and a correspondingly rapid accumulation of fluviatile detritus—so rapid as to preclude the existence of living organisms within the area of deposition.

The total thickness of the Flysch sandstones and shales has been variously estimated at from 10,000 to 20,000 feet; but the thickness of sediments of this character cannot be determined by measurements taken across the apparent bedding planes.

When detrital material is shot into comparatively deep water, as the reclamation of the fringe of the basin proceeds, it is pushed further and further into the basin, each successive layer assuming its proper angle of rest. With the constant recurrence of floods, sands and muds overspread and succeed one another in a pile of alternating sheets.

When fluviatile deposition of this kind begins on a sea-littoral where marine deposition has previously been in progress, the first layers of fluviatile detritus discharged into the sea are laid down parallel with the bedding-planes of the marine deposits; but whenever the filling in has been carried forward so far that there is a sudden drop into deep water, the bedding-plane of the detritus becomes parallel with the angle of rest assumed by the material as it falls over the end of the advancing delta.

The sediments laid down in the shallow waters of the delta are horizontal or possess a gentle slope seaward, but those discharged in the deeper waters at the outer edge of the delta assume an angle of 30° or more. It should, however, be noted that it is only where the accumulation of fluviatile detritus is relatively rapid that this end-tipping, which is merely an exaggerated form of false-bedding, is found. The process can be advantageously studied in the inland lake-basins of New Zealand, North America, and elsewhere.

Distribution of Land and Water.—The beginning of the Tertiary era still found the Tethys or Central Sea in existence, and on its floor and borders

[1] Flysch (a Swiss provincialism)=stratum.

were laid down a great succession of Lower Tertiary deposits, including the Nummulitic Limestone. The Central Sea, as already described, extended from the Atlantic eastwards through the Mediterranean Basin, covered the whole of Southern Europe and North Africa and stretched over Asia Minor, Arabia, Persia, Baluchistan, Himalayan area to Further India; and although shrunken in size since the Cretaceous period, it still formed a great inland sea that girdled half the globe.

In the Middle Tertiary the eastern half of the Central Sea became occupied by the Himalayas, Caucasus, and the mountains of Persia, Arabia, and Asia Minor; and its northern limits were curtailed by the rise of the Carpathians, Apennines, Alps, and Pyrenees.

The crustal corrugation and folding of the Himalayas, Alps, and other great chains continued till the close of the Miocene, when the Central Sea became broken up into disconnected inland seas and salt-water lakes.

In Pliocene and later times, due to the continued recession of the ocean, the Central Sea diminished in size till in our own time the Mediterranean Sea is all that now remains to mark its former existence.

The present distribution of animals and plants tends to show that there was a Tertiary land connection between Europe and North America through the Faroe Islands and Iceland, and between Alaska and North-East Asia across the present Behring Straits. About the same time land-bridges probably joined South Africa, South America, New Zealand, and Australia with the Antarctic continent.

It is a singular fact that the Tertiary mollusca of Chile presents a greater resemblance to the living and fossil mollusca of the Mediterranean Basin than to the mollusca now living on the coast of Chile. The inference to be drawn from this is that the isolation of the Chilian region did not take place till some time between the mid-Tertiary and the beginning of the Pleistocene.

Climate.—The Tertiary climate of Europe and North America was at first warm, and then tropical; but gradually the climate became temperate, and at last cold. This last phase took place in quite late Tertiary times, bringing about the Great Ice Age of the Quaternary.

Similar variations of climate also took place in the Southern Hemisphere.

The changes of climate are indicated by the character of the land animals and plants, and to some extent by the marine faunas. The period of refrigeration witnessed a great advance of the polar ice-sheets, and the accumulation of gigantic glaciers on the higher mountain-chains.

At the advent of the Tertiary era, the climatic zones of the present day were already well established. For a time the rigors of the Arctic regions were replaced by warm-temperate conditions; but in the Late Pliocene Arctic cold once more prevailed.

Local climatic variation among other causes may arise from geographical changes that affect the direction of the tropical oceanic currents. The climatic changes in Greenland and Spitzbergen would tempt the geologist to revise the mythical Atlantis. The lost Atlantis is first mentioned by Plato in his dialogue "Timaeus." It is described as a great island continent, equal in extent to the Libyan Desert and Asia Minor combined. It lay somewhere beyond the Pillars of Hercules—that is, beyond Gibraltar and Ceuta. The Phœnicians are said to have carried on a great trade with it; and at the zenith of its power it was overwhelmed by a tremendous volcanic disturbance and completely engulfed in the sea.

An island-continent, in the mid-Atlantic, would divert the Gulf Stream against the coast of Greenland before crossing to Arctic Europe, and also help

to solve the problem of the dispersal of the land mammals as between Europe and America. For biological and climatic reasons, the existence of an Atlantic continent is almost as necessary to the geologist as the hypothetical Gondwana-Land of the Indian Ocean.

Subdivision.—In the Cainozoic era, climate exercises a more potent influence than ever in the distribution of animals and plants; and in consequence the methods of subdivision and correlation of rock-formations by some characteristic fossils so successfully applied to the Mesozoic and Palæozoic systems can no longer be employed. In these circumstances it became necessary to devise some new method of subdivision in order that the formations in one region should be equivalent in time to those in another region.

The method of classification first suggested in 1830 by the French geologist Deshayes, and subsequently adopted by Lyell, for the chronological subdivision of the Cainozoic rock-formations is based on the proportion of living to extinct forms contained in the complete fauna. The principle underlying this method is that the older a formation is, the fewer living species will it contain; and the younger it is, the greater the number.

When groups of beds in two distant regions are classified as Eocene, it does not necessarily follow that they are contemporaneous, for it is evident that through various physical and climatic conditions a larger proportion of species may contrive to survive in one region than in another. Moreover, the rate of evolution is not the same in the different orders of the animal kingdom.

The age of formations, as determined by the percentage of living species, is comparative rather than actual.

Though the results are merely approximate, the percentage method of classification has proved useful for the subdivision of great thicknesses of fossiliferous marine strata in certain maritime areas. But correlations based on percentages alone must always be regarded with suspicion. The correlation of distant strata should in all cases be based on faunal relationships.

The main divisions of the Cainozoic, or *Neozoic*[1] era as it is sometimes called, are as follows:—

Upper Cainozoic	6. Recent.	
	5. Pleistocene[2]	=mostly recent species.
	4. Pliocene[3]	=majority recent species.
	3. Miocene[4]	=minority recent species.
Lower Cainozoic	2. Oligocene[5]	=few recent species.
	1. Eocene[6]	=dawn of recent species.

The Foraminifera are such persistent organic types that, standing by themselves, they are of little value for the division of the Cainozoic era into time periods; while the higher land vertebrates show such a rapid biological development and limited distribution, combined with a constitution so acutely sensitive to climatic and geographical changes, that they are equally untrustworthy for purposes of subdivision. The more stable and widespread marine mollusca form the best available basis of classification.

[1] Gr. *neos*=new, and *zoe*=life.
[2] Gr. *pleiston*=the most, and *kainos* (*cene*)=recent.
[3] Gr. *pleion*=more, and *kainos*.
[4] Gr. *meion*=less, and *kainos*.
[5] Gr. *oligos*=few, and *kainos*.
[6] Gr. *eos*=the dawn, and *kainos*.

The percentages of living, *i.e.* recent, species of the molluscous fauna used as a basis of classification are as follows :—

Recent	=100 per cent.
Pleistocene	= 90—100 per cent.
Pliocene	= 40— 90 per cent.
Miocene	= 20— 40 per cent.
Oligocene	= 10— 20 per cent.
Eocene	= 3— 10 per cent.

The main divisions of the Cainozoic are sometimes recognised as separate systems, but they represent periods of time so much shorter than the systems of the Palæozoic and Mesozoic eras that they are, by some writers, grouped into two great divisions or systems called the *Palæogene* and *Neogene.* Since the systems are admittedly of unequal value as measures of time, it is unimportant whether we regard the Eocene, Oligocene, etc., as systems or merely as series. Obviously the relative importance of a succession of strata cannot be measured by the thickness of the deposits which it comprises, but by the organic changes that took place during the time occupied in the deposition of the sediments.

Though the Cainozoic may cover a relatively short period of time, it is certain that it has witnessed a more striking and momentous development of organic life and physical changes of greater magnitude than the Mesozoic. Hence, for our present purpose, we will regard the Cainozoic as an era and the main divisions as systems.

EOCENE.

At the close of the Cretaceous there was a recession of the sea all over the globe. Hence the Eocene deposits occupy a smaller area than the Cretaceous ; and shallow water, estuarine and even terrestrial sediments follow the Chalk.

The recession of the sea caused a widespread migration of the Cretaceous life, and no species of mollusc or higher form of life survived till the Eocene. All the forms slowly disappeared or became modified by the development of structural features better adapted to the new conditions and environment.

Distribution.—In Europe the Eocene is mainly distributed in two geographical regions: the *Anglo-Gallic,* which embraces South England, North France, and Belgium ; and the *Alpine* or *Mediterranean,* which in the main follows the former limits of the Central Sea and embraces the whole of Southern Europe and North Africa and a wide zone extending eastward to Further India.

Rocks.—In the Anglo-Gallic region, which at one time spread over a large portion of North-West Europe, the rocks of the Eocene System are mainly loose incoherent sands, clays, and pebbly beds with occasional bands of hard shelly limestone, and in the Alpine region, massive beds of hard limestone, compact sandstones, and shales. The limestones of this region are largely composed of *Nummulites.*

The Nummulites are the most complex of the Foraminifera. They are equatorial in habitat.

Doubtful species of *Nummulites* are recorded from the Upper Jurassic of Bavaria, but the real beginning of the genus and its greatest development was in the Eocene period, during which they lived in the equatorial Central Sea (Tethys) in extraordinary profusion, as witnessed by the massive beds of limestone composed of their remains that extend from Western Europe to the Himalayas and Further India. They are unknown in the Tertiary rocks of Australia, New Zealand, South Africa, and America. Only one or two rare

forms are living, one of which, *N. cummingi*, is found in shallow water in tropical and subtropical seas.

In the Swiss and Maritime Alps, in the Apennines, Carpathians, and eastwards to the Himalayas, the Upper Eocene is also represented by a vast thickness of grey sandstones and shales of the *Flysch* facies. These rocks occur in close association with massive beds of nummulitic limestone, but are themselves practically devoid of all organic remains. The same facies of rocks is also largely developed in California.

The volcanic activity which revived at the close of the Cretaceous continued into the Eocene. The outbursts were local and intermittent. Eocene volcanic rocks occur in North Ireland, West Scotland, Faroe Islands, Iceland, Greenland, and in the States of California, Oregon, Washington, Montana, Wyoming, and Colorado.

Eocene of British Isles.

The Eocene deposits of England occupy two triangular areas in the south-east end of the island, namely, the *London Basin* in the Thames Valley, and the *Hampshire Basin*, with its base lying along the coast of the mainland opposite the Isle of Wight. Outliers occur in the Isle of Wight, Salisbury Plain, Chilterns, and elsewhere, and indicate a former extension of the Eocene strata over the whole of South-East England.

The Eocene beds everywhere rest on Chalk usually without any visible stratigraphical unconformity.

The beds of the London and Hampshire basins exhibit a close relationship both in fauna and lithological sequences, and it is certain that, though now separated by a ridge of chalk, they were all laid down on the floor of the same continuous sea.

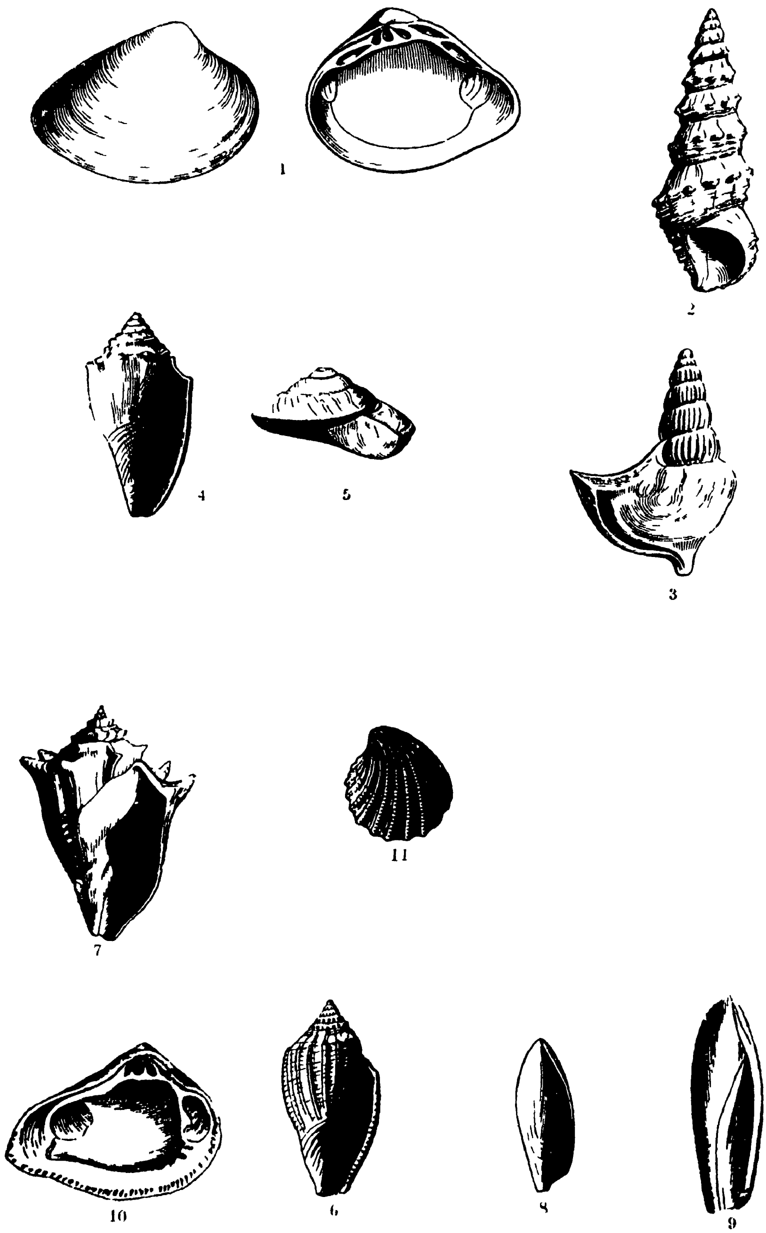
Local Subdivisions.—The subdivisions usually recognised in the two basins are as follows :—

	London Basin.	Hampshire Basin.
Upper Eocene	—	9. Headon Beds.
	—	8. Barton Sands.
	—	7. Barton Clay.
	6 Upper Bagshot Beds.	6. Upper Bracklesham Beds.
Middle Eocene	5. Middle Bagshot Beds.	5. Lower Bracklesham Beds.
Lower Eocene	4. Lower Bagshot Beds.	4. Alum Bay Sands.
	3. London Clay.	3. London Clay.
	2. Woolwich and Reading Beds.	2. Reading Beds.
	1. Thanet Beds.	—

The **Thanet Sands** consist of light-coloured sands which are clayey at the base, and contain glauconitic grains. Where they rest on the Chalk, they contain a basal layer of unworn, green-coated flints, which was apparently formed after the sands were deposited. The flints are the insoluble residuum left behind after the upper layers of Chalk in which they were imbedded had been removed by the action of percolating water. Examples of underground chemical corrosion are not infrequent where limestones are followed by porous sands or sandstones containing moving water.

The fossils of the Thanet Sands are marine and mostly Lamellibranchs and Gasteropods. Among the more abundant forms are *Corbula regulbiensis* and *Aporrhais Sowerbyi* (Plate LV. fig. 3).

The **Woolwich and Reading Beds** vary considerably in character. In



EOCENE FOSSILS.

PLATE LV.

EOCENE FOSSILS.

1. *Cyrena cuneiformis* (Sow.). Woolwich and Reading beds (Plastic Clay). Charlton, Upnor, etc.
2. *Melania (Melanoides) inquinata* (Defr.). Plastic Clay. Woolwich, New Cross, Plumstead.
3. *Chenopus (Aporrhais) Sowerbyi* (Mant.). London Clay Series. Herne Bay, Highgate, Bognor, Watford.
4. *Voluta nodosa* (Sow.). Middle Eocene. Barton, etc.
5. *Phorus extensus* (Sow.). London Clay. Highgate, Sheppey, Bognor, etc.
6. *Voluta ambigua* (Soland.). Middle Eocene. Barton.
7. *Volutilithes athleta* (Sow.). Middle Eocene. Barton, Bracklesham.
8. *Terebellum convolutum* (Lam.). Middle Eocene. Barton, Bracklesham.
9. *Terebellum fusiforme* (Desh.). Barton and Bracklesham.
10. *Crassatella sulcata* (Sow.). Middle Eocene. Barton.
11. *Cardita sulcata* (Brander). Middle Eocene. Barton, Hordwell.

East Kent they consist of marine sands, and in West Kent and Surrey of estuarine sands and grey clays, which may be taken as an indication that the land lay to the westward.

In the Hampshire Basin, only the Reading Sands are present. The *Oldhaven and Blackheath Beds*, which consist of fluviatile pebbly sands and pebbles, are local subdivisions overlying the Woolwich Series.

The **London Clay** is perhaps the most important division of the Eocene in England. It is usually a stiff marine clay of a bluish-grey colour, except at the surface where it weathers to a brown hue. It contains layers of calcareous concretions and nodules of pyrites. In some places crystals of selenite are common. At London, which lies about the centre of the basin, the thickness of the clay is 400 or 500 feet. In the Hampshire Basin the London Clay is more sandy than in the eastern basin.

Fossils are abundant and mostly marine molluscs, crustaceans, fishes, and land plants. Among the molluscs are *Aporrhais Sowerbyi* and *Aturia ziczac*;

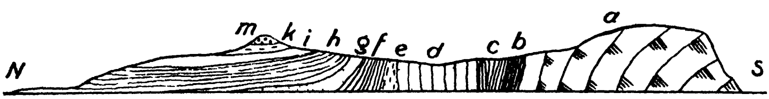


FIG. 219A.—Section across the Isle of Wight. (After H. W. Bristow.)

a. Chalk.—Cretaceous.
b. Reading Beds.
c. London Clay.
d. Lower Bagshot Beds.
e. Bracklesham Beds.
f. Burton Clay.
g. Barton Sand.
(*b*–*g*: Eocene.)

h. Headon Beds.
i. Osborne Beds.
k. Bembridge and Hamstead Beds.
(*h*–*k*: Oligocene.)
m. Gravels.—Recent.

and the genera *Pleurotoma, Fusus, Murex,* and *Natica* are represented by numerous species.

The fishes include many forms of rays (*Myliobatis*), and the ubiquitous sharks (*Lamna, Odontaspis,* etc.). Among the numerous reptilians are turtles, tortoises, crocodiles, and a sea-snake. The remains of several birds have also been found. The mammals include ancestral forms of the tapir, bat, and opossum.

The plants include fan-palms, feather-palms, cactus, fig, elm, poplar, beech, planes, maple, and many other angiosperms.

The land animals and vegetation would indicate the prevalence in the Middle Eocene of a warm, temperate, or semi-tropical climate in the south of England resembling that of Egypt at the present time.

The **Bagshot Beds** are divided into three subdivisions, Lower, Middle, and Upper. They occupy a smaller area than the London Clay, which is probably a result of denudation. The Upper and Lower divisions consist mainly of sandy beds, and the Middle division, of clays. In the London Basin they do not contain many fossils, but the corresponding beds in the Hampshire Basin—the Bracklesham Beds on the coast of Sussex, and the Barton Beds in the Isle of Wight, which occupy a somewhat higher position in the stratigraphical range—contain a rich molluscous fauna which includes *Cardita sulcata* (Plate LV. fig. 12), *Crassatella sulcata* (Plate LV. fig. 11), *Voluta ambigua* (Plate LV. fig. 7), *Volutilithes athleta* (Plate LV. fig. 8), and *Pleurotoma dentata*.

The well-known *Grey Wethers* or *Sarsen stones* of the south of England are

tabular masses of siliceous cement-stone, probably derived from portions of the Reading Beds solidified by the infiltration of siliceous waters.[1]

Contemporaneous Volcanic Activity.—At the time the streams and rivers were discharging their load of detritus into the Anglo-Gallic sea and its estuaries, there was a great display of volcanic activity in the north of Ireland and west coast of Scotland. Successive sheets of lava were poured over the land and formed wide basaltic plateaux.

The Antrim Plateau, which is but the remnant of a greater plateau, extends from Belfast Lough to Lough Foyle, and from the south of Lough Neagh to the Giant's Causeway, and covers an area of about two thousand square miles. The great cliffs which form the striking coastal scenery of the famous Giant's Causeway have been carved out of the edge of a thick sheet of basalt, which exhibits a symmetrical columnar structure of great beauty (fig. 125).

From Antrim the basalts extend to the Islands of Staffa, Mull, Skye, and the other islands of the Inner Hebrides. At Staffa they form the celebrated Fingal's Cave.

These basalts were poured out by successive eruptions, some of which were separated by considerable intervals of quiescence. In these periods of rest subaerial denudation became active, and the neighbouring hollows and lagoons were soon filled with sands and gravels. The surface of the lava-flows also became weathered and disintegrated, and formed soils on which a rank semi-tropical vegetation grew long enough to form peaty deposits that have since become changed into beds of lignite. Later eruptions overwhelmed the forests and covered up the newly formed sediments and peat-bogs.

The plant remains enclosed in the intercalated soils and detrital material comprise various palms, cactus, oak, laurel, and other evergreen trees found in the London Clay.

It is claimed by some writers that the volcanic region of North Ireland and West Scotland belongs to the petrographical province which includes the Faroe Islands, Iceland, and the eastern portion of Greenland.

The volcanic phase of igneous action was followed by a plutonic one. In Central Skye, Southern Rum, South-Eastern Mull, and Northern and Central Arran there were successive intrusions of magmas of decreasing basicity, ranging from peridotites to granites. Most of the plutonic masses have something of the sheet-like or lacoslitic habit.

Eocene of Other Countries.

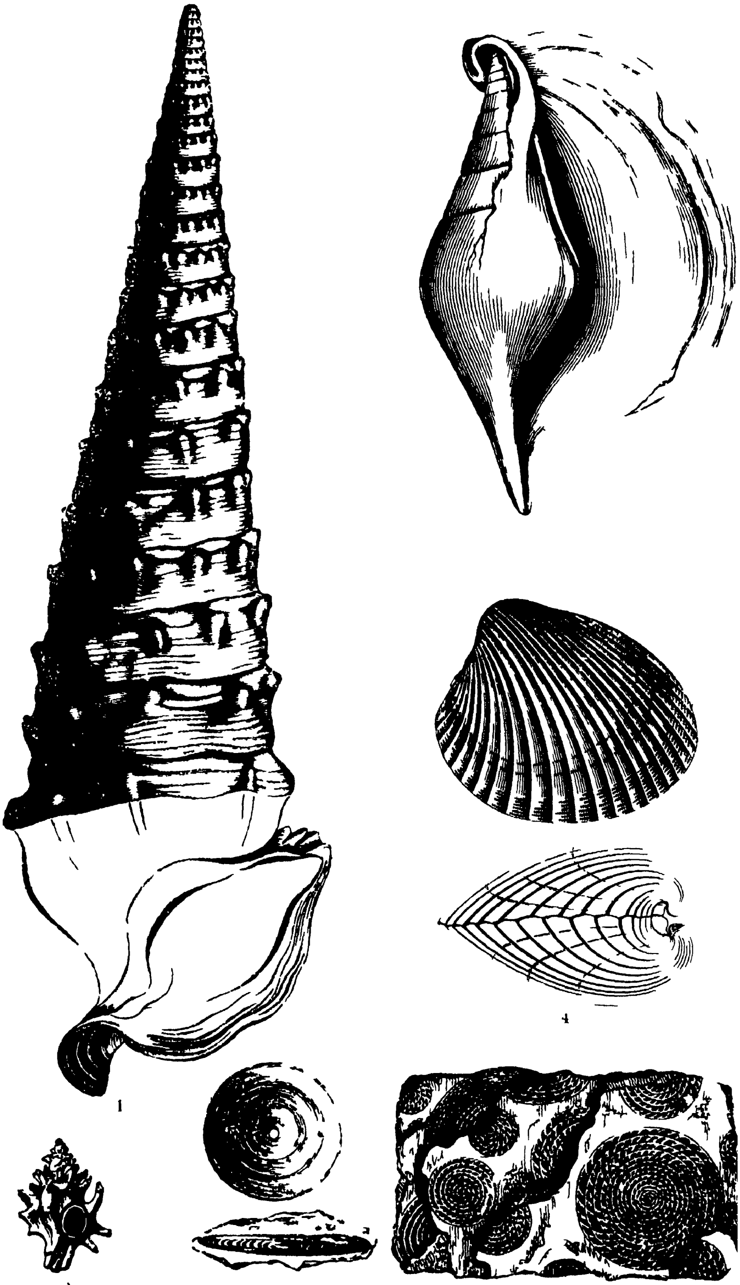
France.—The Eocene System is fully developed in the Paris Tertiary Basin, which is a continuation of the English basins across the Channel. The deposits are mainly marine, but beds of estuarine and freshwater deposits are also present. Molluscs are exceedingly abundant; and the genera *Fusus*, *Pleurotoma*, and *Cerithium* are represented by the greatest number of species.

French geologists recognise three divisions, namely, the Lower, Middle, and Upper.

The *Lower Eocene* consists mainly of estuarine and terrestrial marls, sands, and plastic clay with seams of brown coal.

The *Middle Eocene* is represented by a band of impure shelly limestone, 30 feet thick. This is the principal building-stone in Paris, and hence has

[1] P. G. H. Boswell, "The Stratigraphy and Petrology of the Lower Eocene Deposits of the North-Eastern Part of the London Basin," *Quart. Jour. Geol. Soc. London*, vol. lxxi. pp. 536–91, 1915.



EOCENE FOSSILS

PLATE LVI.

EOCENE FOSSILS.

1. *Cerithium giganteum* (Lam.). Middle Eocene. Bracklesham, Grignon, etc., France.
2. *Rostellaria* (*Hippocrene*) *macroptera* (Lam.). Middle Eocene. Barton, Bracklesham. Lower Eocene (London Clay). Kingston and Whetstone.
3. *Typhis pungens* (Soland.). Middle Eocene. Barton, Alum Bay (Isle of Wight).
4. *Cardita* (*Venericardia*) *planicosta* (Lam.). Middle Eocene. Bracklesham.
5. *Nummulites lævigatus* (Brongn.). Middle Eocene. Bracklesham, Isle of Wight.

become the best-known member of the Eocene in this basin. The lower beds of the limestone contain Nummulites in great abundance; also many sea-urchins and a great assemblage of Lamellibranchs and Gasteropods. Among the last is the gigantic *Cerithium giganteum* (Plate LVI. fig. 1), which sometimes reaches a length of nearly three feet.

The *Upper Eocene* is a marine sand about 48 feet thick, crowded with molluscs. It is intercalated at St. Ouen with a band of freshwater limestone which contains many examples of *Limnæa longiscata.*

Belgium.—The Eocene rocks of Belgium show a similar development to those of the London and Paris Basins, to which they are closely related. The lowest beds at Mons, forming the Montian, a stage entirely missing in Great Britain, contain *Cidaris Tombecki* and other sea-urchins, as well as Lamellibranchs and Gasteropods. These beds, ascribed to the Cretaceous by different authors, are now recognised as the oldest Tertiary.

Southern Europe.—The Eocene deposits laid down on the floor of the great Central Sea extend from Portugal eastward through the Alps, Apennines, Carpathians, and Caucasus to Asia Minor, whence they pass still further east to the Himalayas. On the south side of the Mediterranean they stretch from the Atlas Mountains and Morocco eastwards to Egypt, Libyan Desert, Syria, Palestine, Arabia, and Persia, where they merge into the broad zone passing through Central Asia.

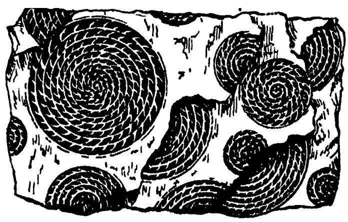


FIG. 220.—Fragment of Nummulitic Limestone.

The deposits laid down in this great Central sea (Tethys) belong to the Alpine or Equatorial facies, and differ vastly from those of the Northern facies as developed in the Anglo-Gallic region. In the first place, the rocks are not loose and incoherent, but mainly masses of compact limestone or hard sandstones and gritty shales of the *Flysch* type. Palæontologically they are characterised by the abundance of Nummulites, which are large disc-shaped Foraminifera provided with a complicated chambered shell (fig. 220).

The Nummulitic Limestone of Eocene age consists of a series of beds of massive limestone, in places 3000 feet thick. It can be traced from the Pyrenees eastwards through the Alps, Carpathians, and Balkan States to Asia Minor. On the south side of the Mediterranean, it stretches far south into the Sahara, Libyan Desert, and Egypt. From Arabia and Asia Minor, as already described, it passes eastward to the Himalayas and Further India, and thence through Java, Sumatra, Borneo, and Philippines. In Egypt it was the chief source of the building-stone used in the construction of the Pyramids, near Cairo.

India.—The Eocene of India belongs, as we have seen, to the Southern or Equatorial facies, and was laid down in the eastern end of the Central Sea. It is principally characterised by the great development of the nummulitic limestones.

The Eocene of India is divided into three stages or series—

Upper Eocene (3)—Khirthar Series.
Middle Eocene (2)—Laki ,,
Lower Eocene (1)—Ranikot ,,

The *Ranikot Series* consists mainly of basal fluviatile sandstones followed by marine beds. It is restricted to a small area in Scind.

The *Laki Series* is in some places sandy, in others calcareous. The well-known Laki Limestone abounds in Foraminifera, of which the genera *Nummulites* and *Alveolina* are prominent. This series is of great economic importance for its valuable coal-seams, which are well developed in the Punjab, Assam, and Baluchistan.

The *Khirthar Series* consists chiefly of limestones which, on the Scind-Baluchistan border, attain a thickness of 3000 feet, and contain some zones remarkably rich in Nummulites, among which *Nummulites lævigatus* (Plate LVI. fig. 5), *N. perforatus*, and *N. complanatus* are the most common.

North America.—Rocks of Eocene age cover large tracts in the United States, and in the main follow the outcrops of the Cretaceous, although they occupy a much smaller area as a result of the recession of the sea which followed the close of the Cretaceous.

They comprise three distinct types of deposits, each occupying a separate geographical region. The marine type is distributed as a fringe along the Atlantic border and Gulf of Mexico; the brackish-water occurs mainly in Washington and Oregon; and the freshwater or lacustrine occupies old lake-basins among the mountains of the Western States.

The marine Eocene beds are typically developed in the Gulf region, and are perhaps best displayed in the State of Alabama, where three divisions are recognised, each richly fossiliferous.

The Eocene beds of Texas are mainly estuarine and partly terrestrial, the latter facies interstratified with layers of salt and gypsum-bearing sediments and seams of lignite. From Texas these beds extend northwards to Arkansas.

The Puget Sound coal-bearing series of Washington is estuarine and terrestrial. It attains a thickness variously estimated at from 10,000 to 20,000 feet.

Numerous patches of coal-bearing strata of Eocene age, usually much disturbed, are scattered around the coastal fringe and maritime valleys of Alaska.

The marine fauna of the North American Eocene System is remarkably rich in molluscs, among which Lamellibranchs and Gasteropods largely predominate. But the most notable feature of this period is the sudden appearance of numerous placental mammals, many of which possess structural features that seem to connect them with the placentals of the present day.

Among the primitive types of land placentals have been found what are believed to be ancestral forms of the rhinoceros, deer, horse, tapir, cat, dog, otter, etc.

The Eocene seas were also peopled with the earliest marine mammals, the cetaceans being represented by whales (Zeuglodons), the sirenians by the dugong.

The Eocene vegetation, as in Europe, indicates a temperate climate in the early part of the period, followed by semi-tropical conditions in the Middle and Upper Eocene.

It is noteworthy that many of the leading types of plant life in the Eocene of North America and Europe are allied to types that still survive in India and Australia.

Australasia.—Marine deposits of Eocene age are unknown throughout Eastern Australia, but are well developed at Mount Gambier and Murray Flats in South Australia, where they contain a rich fauna which includes numerous corals, sea-urchins, brachiopods, Lamellibranchs, and Gasteropods, as well as the remains of fishes and cetaceans.

Eocene deposits are well developed in Tasmania and New Zealand. In the latter they contain seams of bituminous coal of great economic value.

OLIGOCENE.

The Oligocene was formerly regarded as the uppermost portion of the Eocene, with which it is always intimately connected where the full Lower Tertiary succession is present. The separation has no palæontological or lithological basis, and was mainly made in deference to geographical considerations.

In South England, where the Eocene is so well developed, the Oligocene is poorly developed and the Miocene is altogether absent; but in Germany, where the Eocene occupies only small areas, the Oligocene is an important formation. From this we learn that considerable geographical changes took place in North-West Europe at the close of the Eocene. South-East England and North France, which were then covered by the sea, became dry land, and Germany, which was dry land, became inundated by the sea. The uplift in England was balanced by subsidence in Germany.

It was principally owing to these changes of land and sea that it was considered convenient to separate the Oligocene from the Eocene in England and Continental Europe. The Oligocene is not a natural division; and in regions outside Europe where the marine Tertiary succession is complete, the formations arrange themselves into the three natural divisions, Eocene, Miocene, and Pliocene.

Distribution.—With some exceptions the Oligocene occupies the same areas as the Eocene. In Europe it occurs in two distinct geographical provinces, namely, the Northern and the Southern.

The Northern Province embraces the greater portion of the Anglo-Gallic basin, and Northern Germany, and the region of the Rhine Valley between the Black Forest, Vosges, and Taunus. To the latter belongs the basin of Mainz.

The Southern Province covers the region now occupied by the northern border of the Alps, the Apennines, and Carpathians.

In the Northern Province the sediments, as in the Eocene, are mainly represented by loose sands, clays, and pebbly beds with thin-bedded limestones; and in the Southern by sandstones and shales of the Flysch type, together with massive beds of soft pebbly sandstones and coarse conglomerates, which constitute the series of deposits called *Molasse* by Swiss geologists. The lower portion of the Molasse, called *Older Molasse*, is referred to the Oligocene, and the upper portion to the Miocene.

From the Carpathians eastwards through the Balkans, Asia Minor, Arabia, Persia, Baluchistan, the Himalayas, and Burma, the Oligocene is co-extensive with the Eocene.

In Baluchistan and Scind, the strata are mainly unfossiliferous shales of the Flysch facies, and massive beds of nummulitic and coralline limestones.

In North America the Oligocene is closely linked with the Eocene. The marine facies occurs in the Atlantic and Gulf Coastal Plain, while terrestrial deposits with great numbers of fossil mammalia are scattered through the western mountains and plateaus.

Oligocene of British Isles.

The Oligocene strata play an unimportant part in Britain, and are confined to a small area in the Isle of Wight, where they rest conformably on the Eocene, and to the Bovey basin near Newton Abbot in Devon. They are not represented in the London Basin.

The deposits in the Isle of Wight consist mainly of sand, clays, marls, and thin-bedded limestones, and they are partly marine, partly estuarine, and partly freshwater. They were obviously laid down in the Hampshire Eocene delta at a time when distinct but inconsiderable oscillations of the land were in progress.

The subdivisions or stages of the Oligocene of South England are as follows:—

4. Hamstead Beds (marine).
3. Hamstead Beds (freshwater and brackish).
2. Bembridge Beds.
1. Osborne Beds.

Marine Beds are intercalated with the Bembridge and Hamstead Beds. The remaining beds are mainly deltaic and freshwater.

Fossils are found in all the different divisions, and are abundant on some horizons.

The land snails include *Helix* and *Amphidromus*; and among the common forms of pond and river molluscs are the Lamellibranchs *Unio* and *Cyrena*; and of the Gasteropods *Viviparus*, *Limnæa*, and *Planorbis*.

The fossil vertebrates include the remains of rays (*Myliobatis*), sea-snakes, crocodiles, alligators, turtles, and a whale.

The Bembridge Beds have yielded the bones of many mammals, including those of the pachyderms *Palæotherium*,[1] *Anoplotherium*,[2] *Hyopotamus*,[3] and *Chæropotamus*.[4]

The fossil plants are mostly subtropical evergreens, such as fan-palms, feather-palms, conifers, oaks, laurels, and vines.

The nucules of *Chara* (Plate LVII. fig. 11), a freshwater alga, are plentiful in the Bembridge Limestone in the Isle of Wight.

The marine and brackish-water beds contain *Ostrea*, *Cyrena*, *Cytherea*, *Cerithium*, *Melania*, and many other molluscs. In the Osborne Beds *Melania excavata* is a common form.

Bovey Tracey Beds.—These beds are a purely local development. They consist of a series of gravels, sands, and clays with seams of lignite lying in an old lake-basin in the valley of the Teign, between Newton Abbey and Bovey Tracey, in Devonshire. They rest on a highly eroded surface of the Devonian and Carboniferous rocks.

This series of lacustrine sediments varies from 200 to 300 feet thick; and is interesting as representing the continental facies of the Aquitanian in South England.

The fossil plants are numerous and frequently well preserved. They show that the adjacent lands at the close of the Oligocene were clothed with luxuriant subtropical evergreen forests. Among the species are ferns, including *Osmunda* and numerous angiosperms, represented by *Sequoia*, spindle-trees, cinnamon, oak, fig, laurel, willow, and vines.

Oligocene of Continental Europe.

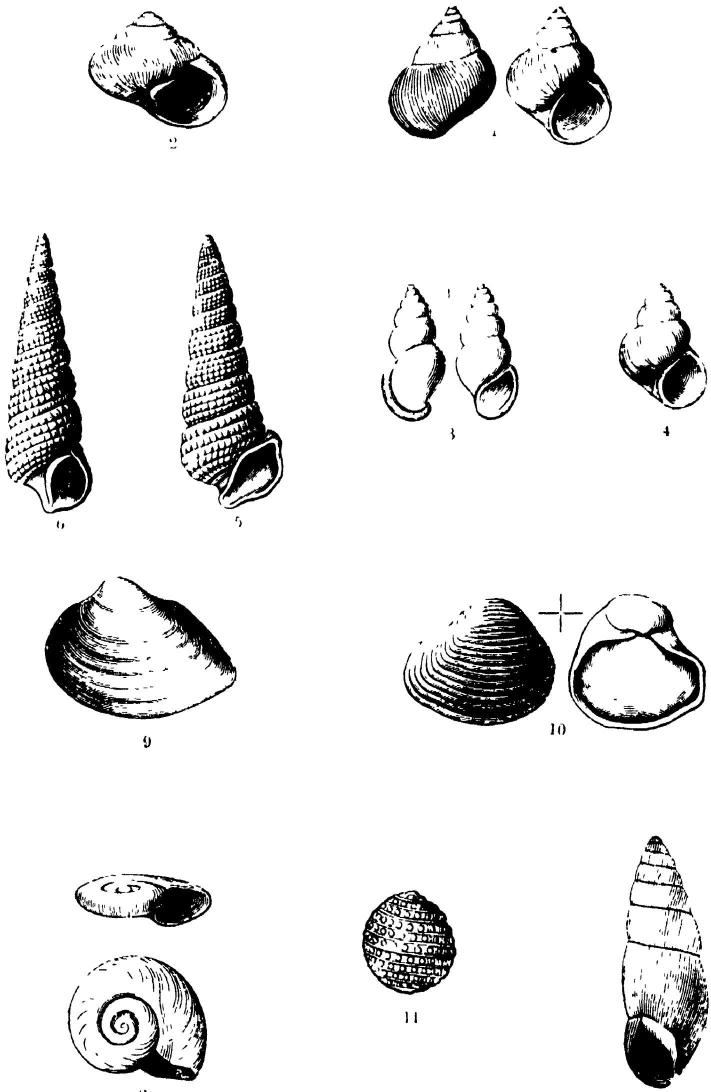
The Oligocene is fully developed in the Paris Basin, where only the middle division is marine; in Belgium, where the strata consist of alternations of

[1] Gr. *palaios*=ancient, and *therion*=an animal.
[2] Gr. *anoplos*=unarmed, and *therion*.
[3] Gr. *hys*=a pig, and *potamus*=a river.
[4] Gr. *choiros*=a pig, and *potamus*.

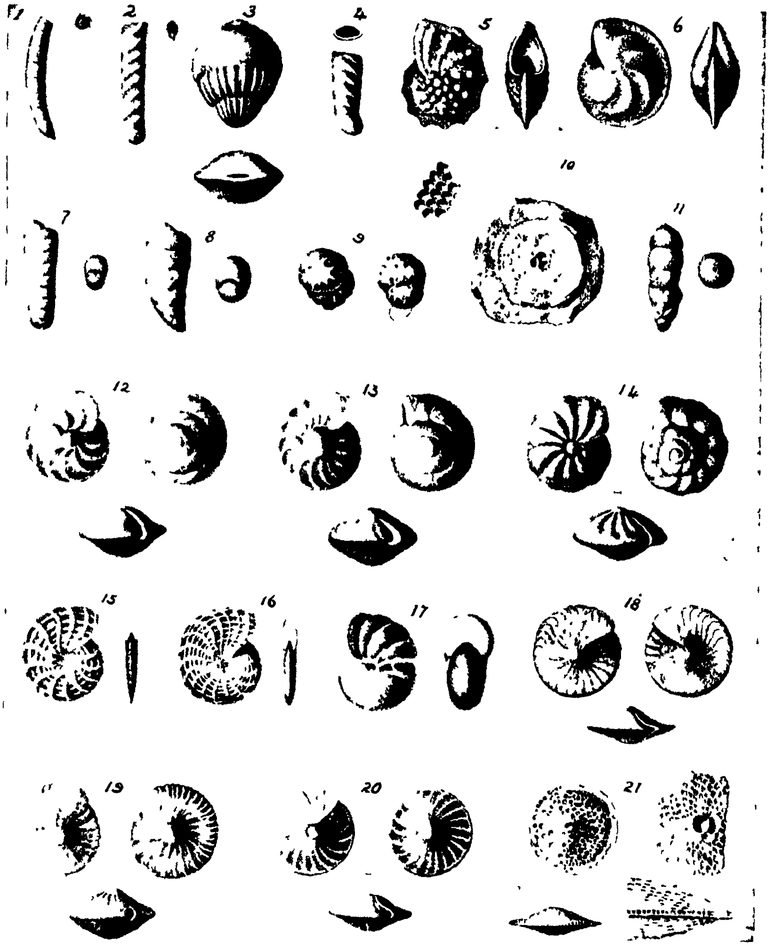
PLATE LVII.

OLIGOCENE FOSSILS.

1. *Paludina orbicularis.* Bembridge Limestone. Isle of Wight.
2. *Helix occlusa* (Edw.). Sconce and Headon.
3. *Rissoa Chastelii* (Nyst). Hempstead, Isle of Wight.
4. *Paludina lenta* (Brander). White Cliff, Hempstead. Middle Eocene. Hordwell.
5. *Cerithium elegans* (Desh.). Hempstead Cliff, Isle of Wight.
6. *Cerithium plicatum* (Brug.). Hempstead.
7. *Bulimus ellipticus* (Sow.). Bembridge Limestone. Isle of Wight. Half natural size.
8. *Planorbis discus* (Edw.). Bembridge Limestone. Isle of Wight.
9. *Cyrena semistriata* (Desh.). Hempstead Cliff, Isle of Wight.
10. *Corbula pisum* (Sow.). Hempstead Cliff, Isle of Wight.
11. *Chara tuberculata* (Lyell). Seed-Vessel. Bembridge Limestone. Isle of Wight.



OLIGOCENE FOSSILS.



FORAMINIFERA. WAITEMATA BEDS, AUCKLAND, NEW ZEALAND. LOWER TERTIARY. (After Karrer.)

Fig. 1. *Dentalina aequalis*, Karr.
„ 2. *Vaginulina recta*, Karr.
„ 3. *Lingulina costata*, d'Orb.
„ 4. *Marginulina neglecta*, Karr.
„ 5. *Cristellaria mammilligera*, Karr.
„ 6. *Robulina regina*, Karr.
„ 7. *Textularia Hayi*, Karr.
„ 8. *Textularia convexa*, Karr.
„ 9. *Textularia minima*, Karr.
„ 10. *Orbitulites incertus*, Karr.
„ 11. *Clavulina elegans*, Karr.

Fig. 12. *Rotalia Novo-Zelandica*, Karr.
„ 13. *Rotalia perforata*, Karr.
„ 14. *Rosalina Makayi*, Karr.
„ 15. *Polystomella Fichtelliana*, d'Orb.
„ 16. *Polystomella tenuissima*, Karr.
„ 17. *Nonionina simplex*, Karr.
„ 18. *Amphistegina Campbelli*, Karr.
„ 19. *Amphistegina Aucklandica*, Karr.
„ 20. *Amphistegina ornatissima*, Karr.
„ 21. *Orbitoides Orakeiensis*, Karr.

marine and freshwater deposits; and in North Germany, where the beds are essentially marine.

Among the fossils, land, freshwater, estuarine, and marine molluscs are plentiful, and also the remains of plants, fishes, and mammals.

The *Lower Oligocene* of the Paris Basin is characterised by mammalian remains, which include *Palæotherium*, *Anoplotherium*, etc.; first described by Cuvier.

The *Middle Oligocene* of the Paris Basin and Rhine Valley contains a rich fauna, which includes *Cerithium plicatum* (Plate LVII. fig. 6), *Buccinum cassidaria*, *Cyrena semistriata*, and *Leda Deshayesiana*. The last is also characteristic of the *Septarian Clay*, which is a well-marked member of the German Middle Oligocene.

The Upper Oligocene of the Paris Basin is freshwater, and contains numerous species of *Helix*, *Viviparus*, *Planorbis*, and *Limnæa*. The marine equivalent of these beds in the Mainz Basin of the Rhine Valley contains *Cerithium plicatum*, *Perna Soldani*, and other molluscs.

The Flysch sandstones and shales of the Southern European Province are practically unfossiliferous, but contain at Glarus a bed of slaty shale crowded with well-preserved fish remains.

The *Molasse Series* of Switzerland rises into high picturesque mountains, as in the Rigi and Rossberg. It consists essentially of fluviatile drifts discharged into a freshwater lake-basin. In many places its sediments have preserved numerous remains of the vegetation that clothed the slopes of the surrounding ranges. Curiously enough, the plants include palms related to an American type, the Californian conifer *Sequoia*, as well as the alder, fig, cinnamon, oak, and many other evergreen forest trees.

The geographical names usually applied to the Oligocene of France, Belgium, Switzerland, North Italy, and regions where that system has been recognised are as follows:—

Upper Oligocene—3.	Aquitanian,	so named from	Aquitania.
Middle Oligocene—2.	Rupelian,	,,	the Rupel River in Belgium.
Lower Oligocene—1.	Tongrian,	,,	Tongres in Limbourg.

Perhaps the most interesting Oligocene deposits in Europe are the amber-bearing beds near Königsberg in Eastern Prussia. The lower beds consist of glauconitic sands with a rich Lower Oligocene fauna, which includes molluscs, sea-urchins, numerous crustaceans, and the teeth of sharks; and the upper beds of lignite-bearing sands.

The amber for which these beds have long been famous is the fossil resin of various pines, especially of *Pinus succinifera*. It is found in what is locally called the *B ue Earth*, not far from the base of the glauconitic sands. It is derived from an older deposit, probably of Eocene age.

The scientific importance of the amber depends on the remarkable number of insects, spiders, etc., and plant remains enclosed in it, usually in a perfect state of preservation. Altogether over 2000 species of insects; and of plants, over 100 Dicotyledons alone have been identified; also palms and other Monocotyledons.

Oligocene of India.

The Oligocene is represented in Baluchistan by the Kojak Shales of the Flysch facies, and in Scind and Baluchistan by massive beds of

fossiliferous marine strata, which are divided into two series, the *Nari* and *Gaj*:—

Lower Miocene—	3. Mekran.
Oligocene	2. Gaj.
	1. Nari.

The Nari Series includes massive beds of Nummulitic Limestone, which are particularly rich in large Foraminifera, some of which attain a diameter of several inches.

The *Gaj Series* consists of shales and coral limestones.

CHAPTER XXXIII.

MIOCENE AND PLIOCENE.

Miocene.

THE Miocene Period witnessed great changes in the distribution of land and water in Europe and Asia, including the uplift of the Pyrenees, Alps, Carpathians, and Himalayas.

At the close of the Miocene the main physiographic features of the Old World, as we now know them, were clearly defined. The British Isles and North France, where Miocene deposits are absent, formed dry land; and Northern Germany, which was mostly covered with the sea in the Oligocene Period, now almost entirely became continental.

In Northern Europe there was widespread uplift, and in Southern Europe the gigantic orogenic movements which folded the Alps and Carpathians were now in progress. The Eocene and Oligocene strata, both marine and deltaic, laid down on the floor and fringe of the Central Sea, became involved in the huge crustal folds of these chains. Moreover, the corrugations, dislocations, and over-thrusts which accompanied the crustal movements cut off portions of the sea, that eventually became freshwater lakes.

The North Sea now came into existence, and marine deposits were laid down on its floor in North Germany, in the provinces of Schleswig-Holstein and Friesland.

Wide arms of the Atlantic filled the basins of the Loire and Garonne, and a long prolongation of the Central Sea spread northward along the margin of the Western Alps, and passed eastwards through Upper Bavaria to the Vienna Basin. Another arm of the Miocene sea stretched round the Carpathians into Moravia, while a greater prolongation spread over South Russia, following a depression, of which the Black Sea and Caspian are the remaining portions.

The Alps and Carpathians were thus completely surrounded by the sea, and stood up as rugged chains near the northern coasts of the Central Sea.

On its south side the Central Sea still overspread large tracts of North-West Africa, and overflowed the maritime lowlands of Spain and Portugal.

The crustal movements that formed the Alps and Carpathians, at the same time raised the floor of the Central Sea in the areas now occupied by Egypt, Syria, Arabia, Asia Minor, and Persia, and uplifted the mountains of Baluchistan and the Himalayas.

This general Miocene uplift broke up the Central Sea, and detached the Mediterranean portion from the Indian Ocean.

The only record of these widespread, mountain-building, crustal move-

ments to be seen in England is the monoclinal fold of the Eocene and Oligocene strata on the north side of the Isle of Wight, to which reference has already been made (figs. 73 and 219A).

In North America the Miocene strata on the Atlantic border and gulf region lie undisturbed, but in the Pacific States they are acutely folded, and in places uplifted to a great height in the Rocky Mountain chain. On the Atlantic side of the continent, there was a slight emergence of the land, as shown by the narrower limits of the Miocene as contrasted with the underlying Eocene.

Fauna and Flora.—The Miocene flora of Europe shows a closer relationship to the existing evergreen floras of India, Australia, and New Zealand than to the existing European deciduous flora. Among the characteristic genera of the Lower Miocene are numerous palms, magnolias, myrtles, laurels, vines, etc., which indicate the prevalence of a warm, subtropical climate. The absence of palms, and the presence of such hardy trees as the oak, elm, beech, etc., in the Upper Miocene, show the advent of cooler conditions in the later half of this period.

Foraminifera are still numerous, but the genus *Nummulites* is relatively scarce. On the other hand, *Amphistegina*, which appeared in the Upper Cretaceous, is abundant in all the Miocene seas, and in some areas forms massive limestones. With it are associated the genera *Lepidocyclina* and *Cycloclypeus*, the former of zonal value.

The character of the molluscous fauna confirms the evidence of the flora. Among the common genera we have *Murex*, *Ancillaria*, *Cassis*, *Mitra*, *Terebra*, *Arca*, *Mactra*, *Panopæa*, *Pectunculus*, *Tapes*, *Tellina*, *Dosinia*, and other forms that abound in warm seas.

In Spitzbergen, Iceland, Greenland, and North Alaska, the fossil plants are also subtropical, but in Japan, Kamtschatka, Saghalien, and Eastern Siberia the flora indicates a somewhat cooler temperature than the present.

The distinguishing feature of the Miocene fauna is the appearance of the gigantic Proboscidians, *Dinotherium* and *Mastodon*, the last related to the true elephant, which did not appear till later. Among other Miocene mammals are many species of rhinoceros, hippopotamus, and deer; also whales and dolphins.

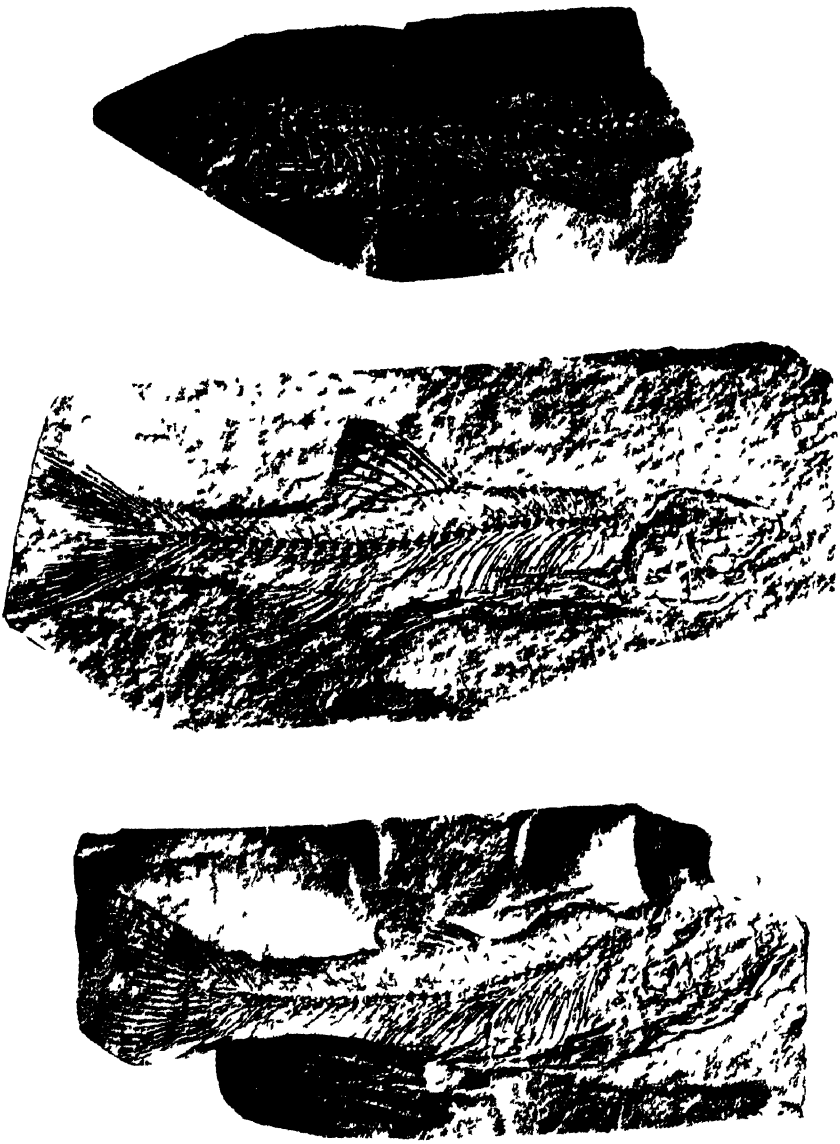
The Miocene mammalian fauna is prolific and varied, and marked by a conspicuous development of the ungulates and carnivores. The rodents are not so prominent as in the Eocene; and the insectivores and lemuroids show a notable decline.

The marine mollusca show an increasing relationship to existing forms. In Europe and North America frequently a third of the fossil species are living forms.

The zonal distribution of the marine faunas is conspicuous both in North America and Europe. Generally the Northern or Maryland fauna is related to the North European, and the Gulf fauna to the Mediterranean.

Miocene of Continental Europe.

France.—Deposits of Miocene age are unknown in Britain, but they are typically developed in France in the district of Touraine, traversed by the rivers Loire, Indre, and Cher. Here they occur in isolated and widely-separated patches of sediments that are mostly marine. They form a sheet that seldom



C

FOSSIL FISH FROM THE ESMERALDA FORMATION, MIOCENE

(*Leuciscus Turneri*, U. S. Geol. Survey.)

exceeds a thickness of 50 feet, and is locally known as *faluns*, from its fertilising qualities as a dressing for the land.

This deposit contains numerous corals, and over 300 species of molluscs, of which about 25 per cent. are identical with living forms.

The mammals include *Rhinoceros*, *Hippopotamus*, *Chœropotamus*, and *Mastodon*.

Vienna Basin.—This great basin is bounded by the Eastern Alps, the plateau of Bohemia and Moravia, and the Western Carpathians. The group of beds contained in it are divided into two series—

2. Sarmatian Series.
1. Mediterranean Series.

This basin began as a salt-water sea and gradually became freshwater.

The deposits of the *Mediterranean Series* vary considerably in different places. Generally they consist of limestones, clays, marls, and sandstones. The Leithakalk is a limestone consisting mainly of reef-building corals and corallines, bryozoans, and Foraminifera.

Marine molluscs are particularly abundant in this series, and of 1000 species many still survive in the Mediterranean and west coast of Africa.

The flora, like the fauna, possesses a subtropical aspect.

In the arms of the sea cut off from the great Central Sea, there accumulated remarkable deposits of rock-salt, gypsum, and anhydrite, the most famous of which is that at Wieliczka in Poland, on the northern flank of the Carpathians, near Cracow.

The *Sarmatian* is mainly composed of fresh- and brackish-water sediments, with some intercalating marine beds, from which it would appear that the general uplift of this stage was accompanied by minor oscillations.

Corals, bryozoans, Foraminifera, and sea-urchins, so abundant in the underlying stage, are rare in the Sarmatian, the muddy estuarine conditions being eminently unfavourable for their growth.

Palms are absent among the vegetation of this time, and the Indian forms predominate over the American types.

Switzerland.—The *Swiss Molasse* occupies the whole area between the Alps and the Jura. Near the former it consists of coarse shore-conglomerates, which, with increasing distance seaward, pass into sandy and clayey sediments. The progressive uplift of the Alps continued into the Pliocene, and the conglomerates now lie at a height of 6000 feet, where they exhibit little or no departure from the original horizontal position in which they were deposited.

The *Lower Molasse*, frequently called the *Grey Molasse*, contains numerous plant remains, mainly subtropical, and a marine bed with *Ostrea*, *Venus*, *Murex*, and *Cerithium*. It is succeeded by the true or *St. Gallen Molasse*, which contains a rich molluscous fauna comprising some 1200 species, of which about one-third are still living.

The St. Gallen stage is followed conformably by the *Upper Freshwater Molasse*, with *Melania*, *Unio*, etc., and seams of brown coal.

In the Tortonian stage the land surrounding the lake was clothed with a luxuriant vegetation, and peopled with a great assemblage of land animals, which included the tapir, mastodon, rhinoceros, deer, apes, opossums, three-toes horse, squirrels, hares, beavers, and the huge *Dinotherium* which frequented the jungle lands fringing the lake. The waters of the lake teemed with fishes, and the shallow pools and mud-banks were frequented by crocodiles.

The three main subdivisions of the Molasse placed in consecutive order are as follows:—

3. Upper Freshwater Molasse—Tortonian (Sarmatian).
2. St. Gallen Molasse (Marine)—Helvetian.
1. Grey Molasse (Lower Freshwater Stage)—Mayencian.

India.—As previously said in last chapter, the Gaj Series of uppermost Oligocene age is conformably followed by the *Mekran Series* of Older Miocene date, which is well developed along the Mekran coast, in the islands of the Persian Gulf, Irawadi Valley in Burma, and Andaman Islands.

The strata consist of clays, sandstones, and conglomerates of the Flysch facies, intercalated with a few calcareous bands.

The characteristic Foraminifera are *Nummulites* and *Amphistegina*. The uppermost beds contain many large pectens.

Towards the close of the Miocene, the Flysch strata were deeply involved in the great folds that marked the final uplift of the Himalayas. The crustal movement of this date broke up the great Central Sea into disconnected inland seas, and severed the Mediterranean from the Indian Ocean, as before mentioned.

The Lower Miocene rocks of India do not possess much economic importance apart from the associated *Pegu* System, which contains valuable oil-bearing strata in Burma and Assam, as well as deposits of salt in the Salt Range in the Punjab.

North America. — The Miocene strata of North America are typically developed on the Atlantic coastal fringe and around the Gulf of Mexico. They dip gently seaward, and in some regions are largely obscured by later accumulations.

In many places along the Atlantic fringe, the Miocene beds appear to rest unconformably on the Eocene (Oligocene), but the stratigraphical break is slight.

Along the Atlantic coast, they are grouped under the name *Chesapeake Series*. For the most part they consist of loose sands, clays, and shelly marls that enclose a rich fauna.

In the Gulf region the Florida Limestone has been largely replaced by rock-phosphate deposits of great extent.

The Miocene of the Pacific Coast, sometimes called the Vagueros and the Monterey Series, is restricted to a narrow fringe skirting the coast-line; but strata of this age also invade the Central Valley of California.

In the mountains south of San Francisco the Vagueros Series of California rests unconformably on the Oligocene. It consists mainly of shales, and sandstones with a notable quantity of volcanic ash.

A striking feature is the extraordinary thickness of the shales, 4000 feet, which are largely composed of siliceous diatoms. The thickness of the whole series has been estimated at from 5000 to 7000 feet.

The Miocene System is of great economic importance as one of the oil-bearing formations of California. The older gold-bearing gravels of that State are supposed to be Miocene, and great accumulations of lacustrine deposits occur in the old lake-basins east of the Sierras, and also in Nevada and Montana.

Volcanic activity was conspicuous throughout the whole of the Miocene, and towards the close of the period culminated in gigantic effusions of basaltic lavas. Evidences of volcanic eruptions are abundant in all the Pacific States, in Columbia, and in the Yellowstone National Park, where forests were overwhelmed by ashes, and in favourable situations the tree trunks were silicified.

PLATE LX.

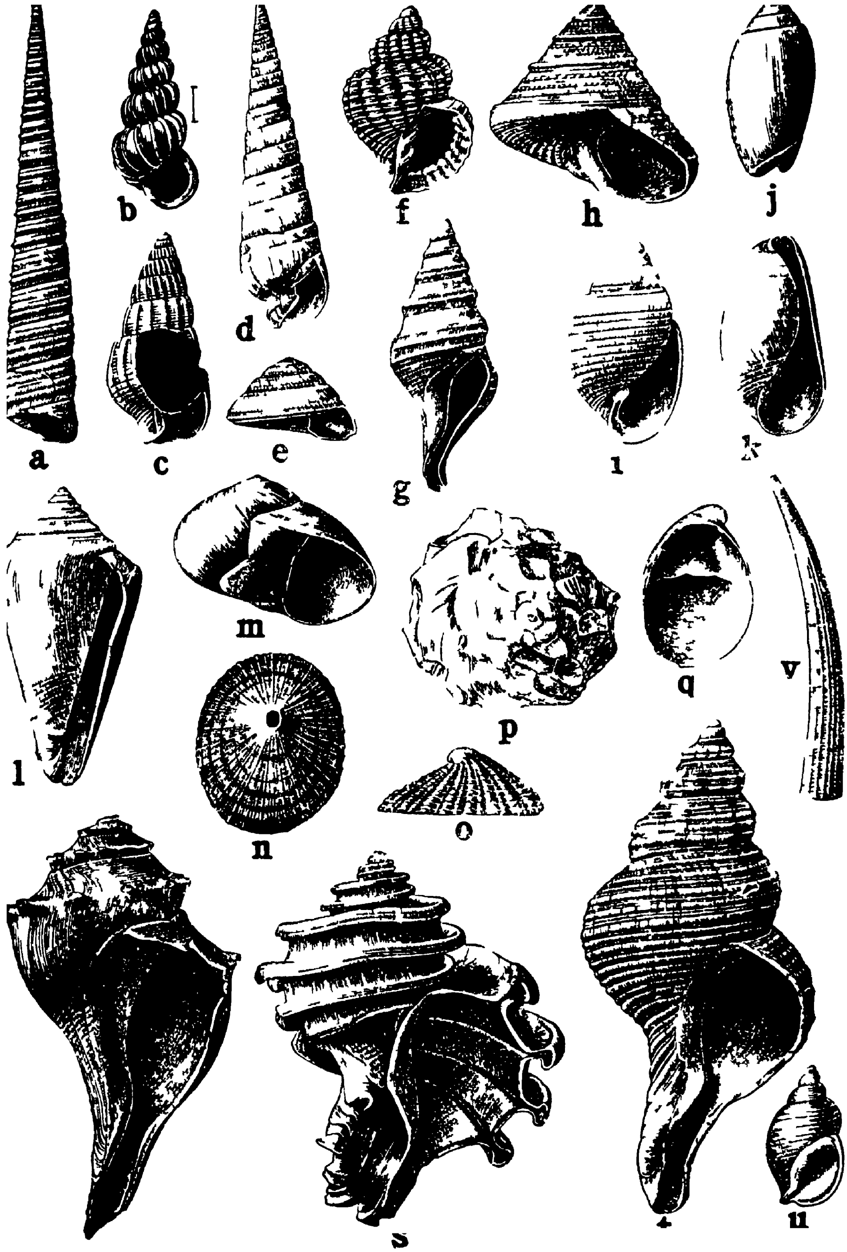
MIOCENE GASTEROPODS.

a, *Turritella variabilis* (Conrad).
b, *Scala sayana* (Dall).
c, *Nassa marylandica* (Martin).
d, *Terebra unilineata* (Conrad).
e, *Solarium trilineatum* (Conrad).
f, *Cancellaria alternata* (Conrad).
g, *Surcula biscatinaria* (Conrad).
h, *Calliostoma philanthropus* (Conrad).
i, *Actæon schilohensis* (Whitfield).
j, *Oliva litterata* (Lamarck).
k, *Retusa* (*Cylichnina*) *conulus* (Deshayes).
l, *Conus diluvianus* (Green).
m, *Polynices* (*Neverita*) *duplicatus* (Say).
n, *Fissuridea alticosta* (Conrad).
o, *Fissuridea griscomi* (Conrad).
p, *Xenophora conchyliophora* (Born.).
q, *Crepidula fornicata* (Linné).
r, *Fulgur spiniger* (Conrad var.).
s, *Ecphora quadricostata* (Say).
t, *Siphonalia marylandica* (Martin).
u, *Ilyanassa* (?) (*Paranassa*) *porcina* (Say).

SCAPHOPOD.

v, *Dentalium attenuatum* (Say).

(After Maryland Geological Survey.)



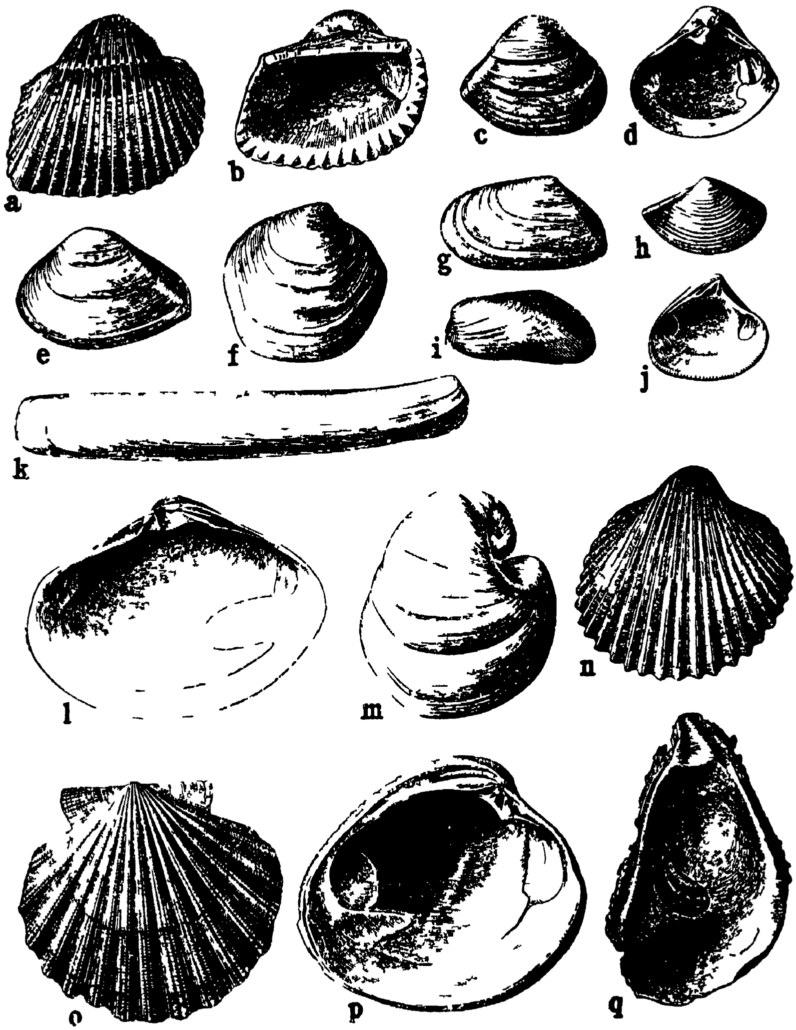
MIOCENE GASTROPODS

PLATE LXI.

MIOCENE LAMELLIBRANCHS.

a and *b*, *Arca* (*Scapharca*) *staminea* (Say).
c and *d*, *Corbula idonea* (Conrad).
e, *Crassatellites marylandicus* (Conrad).
f, *Phacoides* (*Pseudomiltha*) *foremani* (Conrad).
g, *Tellina* (*Angulus*) *producta* (Conrad).
h, *Leda concentrica* (Say).
i, *Modiola dalli* (Glenn).
j, *Astarte thomassii* (Conrad)
k, *Ensis directus* (Conrad).
l, *Spisula* (*Hemimactra*) *marylandica* (Dall).
m, *Isocardia markoei* (Conrad).
n, *Cardium* (*Cerastoderma*) *leptopleurum* (Conrad)
o, *Pecten* (*Chlamys*) *madisonius* (Say).
p, *Venus ducatelli* (Conrad).
q, *Ostrea carolinensis* (Conrad).

(After Maryland Geological Survey.)



MIOCENE LAMELLIBRANCHS

Altogether during the Middle Tertiary, from 200,000 to 300,000 square miles of the western part of the United States were covered with sheets of basaltic lava.

In the Western States the Miocene was a period of great crustal disturbance; and to this date is assigned the orogenic movements which uplifted the Cordilleran chains, and deformed, partly by folding and partly by faulting, the rocks of the Northern Sierras and Great Basin. In the latter region the crustal movements were accompanied or succeeded by violent volcanic outbursts.

Greenland.—In West Greenland, now covered with polar ice and shaded by the long polar night, the plant beds exposed on the coasts of the peninsulas Nugsuak, Svartenhuk, and Tagnerit, and on the islands Disco and Flareö, contain a prolific evergreen subtropical flora. Of 200 species, about half are forest trees, such as the evergreen oak, beech, planes, poplar, maple, walnut, lime, magnolia, and many conifers, including the giant *Sequoia*. *Sequoia Langsdorfi*, *Taxodium distichum*, and *Populus arctica* are the most common species. This flora was ascribed by Heer to the Miocene, but by later authors to the Eocene.

The Miocene plant beds of Spitzbergen, within 12° of the pole, contain an evergreen vegetation resembling much that of Greenland. From this it would appear that the whole of the polar region on this side of the Northern Hemisphere was covered in that period with rank subtropical forests and jungle.

The existence of coal-seams in the Antarctic continent points to similar changes of temperature in the South Polar regions.

The climatic changes that have taken place in past geological times present one of the most difficult problems that confront the geologist.

Australia.—Marine deposits of Miocene of younger date are unknown in Queensland and New South Wales, which, since the Eocene, have remained dry land. In the south-east and southern parts of the continent Miocene beds are extensively developed. In the State of Victoria they cover large tracts, more particularly in Gippsland, where the basal beds of the system contain thick seams of brown coal, one of which at Latrobe shows a thickness of 90 feet.

Near Geelong, the Janjukian series of Victoria includes an extensive development of Polyzoan limestone, associated with beds rich in Foraminifera. Chapman believes that the nummuloid forms of the latter afford convincing proof of the homotaxial relationship of the Janjukian and Miocene of Southern Europe, India, Borneo, and New Hebrides.[1]

Miocene beds are sparingly displayed in Tasmania, but at one time they probably covered a considerable area. At Table Cape the deposits contain a rich molluscous fauna as well as the remains of the primitive marsupial *Wynyardia*.

Marine strata of probably Miocene age occur as a fringe on the Great Australian Bight.

Except in Victoria and a corner of Tasmania, practically the whole of Australia was dry land throughout the Miocene and younger Cainozoic. The conditions of deposition were mainly continental; hence the deposits of this period are mostly sands, gravels, and clays deposited in inland basins, or washed into hollows by torrential rains. There was widespread volcanic activity in the Middle Cainozoic, particularly in the eastern side of the continent. Floods of basaltic lavas spread over the country and streamed down the valleys, where they covered up the gold-bearing gravels and other detrital material. The buried gravels form the famous *deep-leads* of the State of Victoria.

[1] F. Chapman, *Proc. Roy. Soc. Vict.*, vol. xxii., part 11, 1910; and J. Park, *Geology of New Zealand*, 1910, p. 122.

New Zealand.—Miocene strata cover large tracts in both the main islands. The lower beds are terrestrial sands and conglomerates that contain valuable seams of brown coals. They are followed by estuarine clayey and sandy beds. The uppermost beds are marine limestones mainly composed of Polyzoa and Foraminifera. They comprise the great Oamaruian system which has been divided into five stages—

Oamaruian System	5. Awamoan.
	4. Hutchinsonian.
	3. Ototaran.
	2. Waiarekan.
	1. Ngaparan.

The *Ngaparan*[1] are mainly terrestrial or shore deposits comprising quartzose sands and conglomerates that are intercalated with seams of lignite.

The *Waiarekan* consists of marine clays and sandy beds. The lowest or *Bortonian* stage contains a large assemblage of molluscs, among which Gasteropods are the dominant forms. Towards the close of the Waiarekan there began, off the coast of North Otago, a series of submarine volcanic eruptions that continued, with intervals of quiescence, till the close of the Hutchinsonian. The basaltic lavas intercalated with the tuffs of the Waiarekan exhibit a well-developed pillow-structure. In the tuffs there occurs a large branching coral, *Oculina oamaruensis* (Park), that is closely related to *O. mississippiensis* (Conrad, 1900) from the Vicksburgian Oligocene of the Lower Mississippi.

The *Ototaran* comprises the valuable Oamaru building-stone, composed of Polyzoa and Foraminifera. The maximum thickness of this beautiful limestone is about 120 feet. It is a Miocene polyzoan reef that grew on an off-shore platform of tuff. During its growth there was a renewal of volcanic activity on its seaward side, and it became intercalated with a bed of tuff that tapers like a wedge on the landward side till it eventually disappears. This ash-bed contains a rich molluscan fauna, among which the large Nautilus, *Aturia australis*, and many brachiopods are characteristic. The Ototaran beds at Kakanui and Brighton yielded the remains of the gigantic penguin *Palæeudyptes antarctica* Huxley. When the volcanic eruptions ceased, the polyzoan larvæ once more invaded this area, and established themselves on the even surface of the newly formed tuff-platform. The Oamaru building-stone, though mainly composed of polyzoans and Foraminifera, contains molluscs, brachiopods, and echinoderms, all of which are extinct; but the intercalated tuff contains the littoral molluscs of this stage, of which 28 per cent. are living forms. According to the fossils it contains, the Oamaru stone might be placed in the Cretaceous period, but the molluscan fauna that invaded this area during the accumulation of the tuffs, intercalated with it, confirms the position assigned to it by the fossiliferous horizons underlying and overlaying it.

The *Hutchinsonian* stage consists of glauconitic greensands, impure limestone bands, and tuffs. These are overlain by calcareous sandy beds that pass into an impure limestone called the Waitaki Stone. The greensands are crowded with brachiopods, among which *Pachymugas parki* (Hutton) is the dominant form. The molluscs include *Pecten huttoni*, and *Lima lævigata*. Corals are represented by *Isis*, which in places occurs in great abundance, *Trochocyathus*, and *Flabellum*. The Upper Hutchinsonian, or Waitaki Stone, contains an abundant molluscan fauna, among which *Pecten huttoni* is conspicuous. Cetacean remains are also common.

The *Awamoan* stage consists of sandy beds and marine clays from which

[1] "Geology of Oamaru District," *Bull.* 20, *N.Z. Geol. Surv.*, 1918, pp. 1–119.

270 species of molluscs have been identified, and of these 35 per cent. are still living. Among the extinct forms are *Cucullæa alta* (Sow.), *Limopsis insolita* (Sow.), *Pecten huttoni* (Park), and *Natica solida* (Sow.), all of which range from the Ototaran to the Awamoan.

Generally the Miocene strata contour around the coasts of both islands. They are mostly undisturbed or dip gently towards the sea. In West Nelson they have been raised by a series of powerful parallel faults in step-like blocks to a height of 3500 feet above the sea. In East Nelson they are overthrust and involved in the overturned folds of the Triassic rocks.

Economically, the Oamaruian system of New Zealand is important on account of the valuable seams of brown coal which it contains.

South America.—The Santa Cruz Tertiary beds of Patagonia contain many molluscan forms either common to, or closely allied with, those of the New Zealand Oamaruian [1] and Southern Australian Tertiary deposits. But it should be noted that Ortmann suggests that the Magellanian beds, the lower series, are Upper Eocene or Oligocene, and the Patagonian beds, the upper series, Lower Miocene in age.[2] On the other hand, on the evidence of the fish, encrinoid, and coral remains, Ameghino places the Patagonian beds in the Eocene.[3]

Wilckens has urged that the Magellanian beds are of the same (Oligocene or Miocene) age as the Patagonian. Ameghino was inclined to give too high an age to most of the deposits of Patagonia. He erroneously assigned a Cretaceous age to the Mammalian faunas of the older Patagonian Tertiary.

Antarctic Region.—Tertiary strata occurs at Seymour Island, near Graham's Land, containing a rich molluscous fauna considered by Wilckens to be Upper Oligocene or Lower Miocene.

Pliocene.

At the close of the Miocene there was a general retreat of the sea throughout the whole globe, and in the Pliocene the continents began to assume the definite forms they now possess. It is only in those areas where the Pliocene sea-floor has been uplifted and has escaped complete destruction by denudation that marine deposits of that period are exhibited for our examination. And since upward earth-movements of considerable magnitude have not been general or even widespread in the latest Cainozoic, the amount of dry land now occupied by Pliocene marine strata is relatively small.

The bulk of the Pliocene beds to which we have access are lacustrine and fluviatile deposits of the Continental facies that have accumulated in inland basins and river-valleys. In many places these terrestrial deposits, which are mostly loose, unconsolidated drifts, owe their preservation to a protecting cover of basalt, rhyolite, or other igneous rock.

Of the existing dry land forming Northern Europe, only small areas in East England, Belgium, and North France were covered with the Pliocene sea. Germany, which was mainly dry land in the Miocene, became wholly dry land in the Pliocene ; hence marine beds of Pliocene age are not represented among the rock-formation of that region.

In Southern Europe, around the Mediterranean Basin, the sea encroached on the maritime borders of Spain, Algeria, and Greece, and covered large tracts in Sicily, Central and South Italy.

In North America there was the same general recession of the sea as in Europe;

[1] *Rept. Princeton Univ. Exped.*, 1896–99, vol. iv., part ii., 1902.
[2] *Op. supra cit.*, p. 297.
[3] *Anales del Museo Nacional de Buenos Aires*, ser. iii., vol. viii., 1906.

and since the sea-floor has not been uplifted to any extent since the Pliocene, marine strata of that date are but poorly represented on this continent, and occur only as a narrow interrupted fringe bordering the Atlantic and Gulf coasts. On the other hand, detrital deposits of the Continental facies are well developed in the old lake-basins, and along the Atlantic and Gulf maritime borders.

A general recession of the sea took place in India, Australia, South Africa, and South America, and it is only where uplift has taken place that Pliocene strata are exposed at the surface.

Pliocene strata are well represented in the North Island of New Zealand, but are absent in the South Island. From this we learn that a general upward movement took place in the south at the close of the Miocene, and did not affect the North Island till the close of the Pliocene. Since then the Pliocene marine strata of the North Island have been uplifted to an elevation of 3000 feet on the flanks of the main chain. It was this general uplift that ushered in the intense glaciation that affected New Zealand in the Pleistocene.

The Pliocene was a period of notable volcanic activity in Western North America, India, Australia, and New Zealand.

Fauna and Flora.—Most of the molluscs and other invertebrates of the Pliocene fauna are recent species ; but of the vertebrates, almost all the species and even many of the genera are extinct.

Where the Cainozoic succession is complete, the Pliocene follows the Miocene conformably, and is conformably followed by the Pleistocene. The limits of these systems are quite artificial, and the faunas show a progressive organic development when passing upwards from one system to the other.

Perhaps the most notable feature of the Pliocene land fauna is the presence of the large extinct Proboscidians *Dinotherium* [1] and *Mastodon.* [2] Other mammals are very abundant, and include many species of rhinoceros, deer, antelopes, giraffes, ox, cat, bear, fox, porcupine, beaver, and various apes. The true elephant, *Elephas meridionalis*, appears about the close of the period.

The Equidæ are represented by the existing horse, *Equus*, and by the horse-like *Hippotherium gracile* with three toes on each foot, only the central toe reaching the ground.

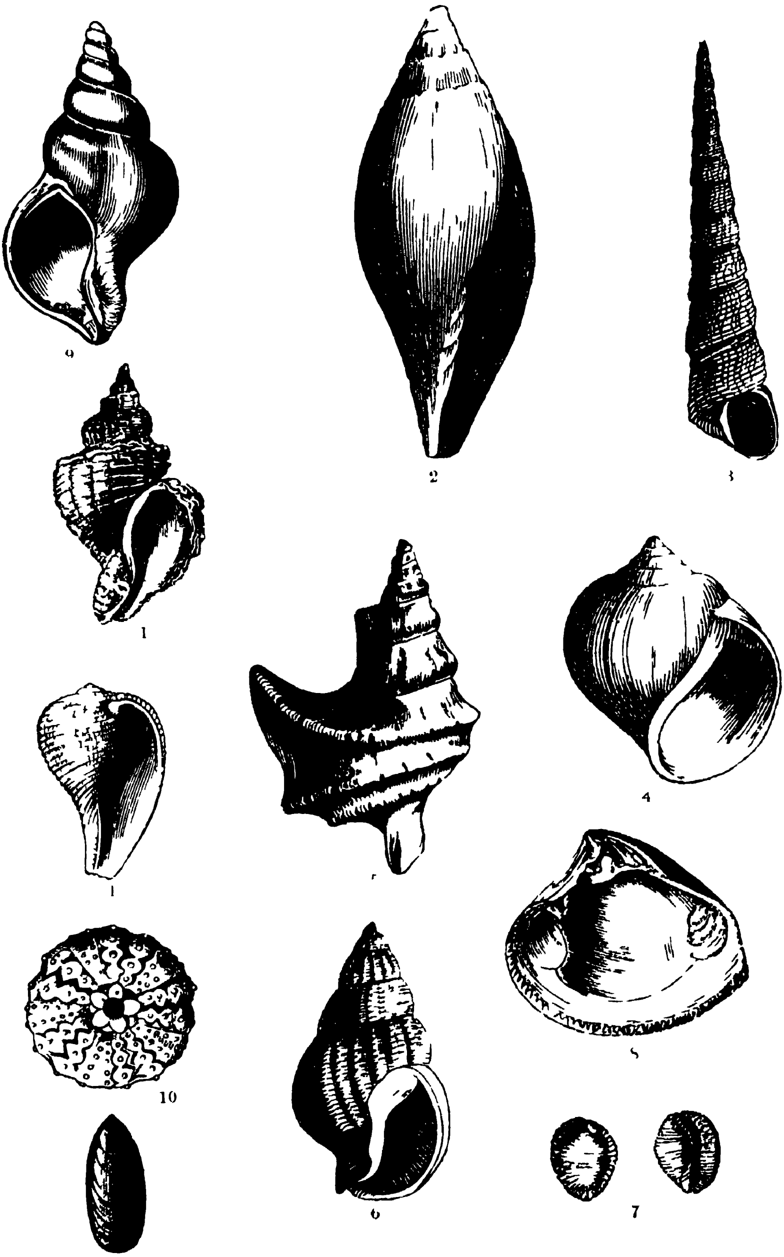
The marine fauna of Southern Europe closely approaches that of the living Mediterranean fauna, and in North-West Europe that of the boreal seas. At the same time many Arctic species appear in the Pliocene deposits of both Italy and England.

Foraminifera, corals, and bryozoans are exceedingly abundant, and the molluscous fauna is very prolific, particularly in Lamellibranchs and Gastero-pods, of which about 90 per cent. are still living.

British Isles.—The only important Pliocene deposits in England occur as a coastal strip in East Anglia, where they are well exposed in the sea-cliffs and beaches from Walton in Essex to Weybourn, north-west of Cromer in Norfolk. A few small patches survive on the Downs of East Kent, and a small deposit occurs at St. Erth in Cornwall.

Newer Pliocene	7. Cromer Forest Bed Series.
	6. Weybourn Crag.
	5. Chillesford Clays.
	4. Norwich Crag.
	3. Red Crag.
	2. Coralline Crag.
Older Pliocene—	1. Lenham Beds.

[1] Gr. *deinos*=terrible, and *therion*=an animal.
[2] Gr. *mastos*=nipple, and *odous*=tooth.



PLIOCENE FOSSILS. (*Crag.*)

PLATE LXII

PLIOCENE FOSSILS.

(Crag.)

1. *Purpura (Polytropalicus) tetragona* (Sow.). Red Crag. Walton on the Naze, Sutton.
2. *Scaphella Lamberti* (Sow.). Coralline and Red Crag. Felixstowe, Walton, Ramsholt.
3. *Turritella incrassata* (Sow.). Coralline and Red Crag. Sutton, Walton, Gedgrave, and Recent.
4. *Natica* sp. Red Crag. Walton.
5. *Aporrhais pes-pelicani* (Linn.). Coralline and Red Crag, Post-Pliocene and Recent Norfolk, Clyde, Sutton, Ramsholt, Newbourn, and Gedgrave.
6. *Buccinum undatum* (Linn.). Coralline Crag. Ramsholt. Red Crag. Sutton, Walton. Mam-Crag. Yorkshire and Recent.
7. *Trivia (Cypræa) europæa* (Mont.). Red and Coralline Crag. Sutton and Recent.
8. *Astarte Basterotii* (Lajonk). Red Crag. Sutton and Felixstowe. Coralline. Ramsholt and Sudburn.
9. *Chrysodomus contrarius* (Linn.), the left-handed or sinistral form of *Chr. antiquus* (Linn.). Red Crag. Walton. Coralline Crag. Bramerton and Recent.
10. *Temnechinus excavatus* (Wood). Coralline Crag. Ramsholt, Suffolk.
11. *Lingula Dumortieri* (Nyst). Coralline Crag. Sutton. (Antwerp Crag.)
12. *Pyrula reticulata* (Lam.). Coralline Crag. Ramsholt.

The different subdivisions are seldom found superimposed on one another; but proceeding northwards along the coast from Walton we pass successively from older to younger beds. From this it would appear that the deposits were laid down on the littoral of a sea, slowly retreating northwards.

The fauna of the Older Pliocene is essentially that of a warm sea, and of the Newer Pliocene of boreal waters.

The molluscous fauna of the older Pliocene comprises a large proportion of southern forms. But the uplift which caused the northward retreat of the sea cut off communication with the southern sea about the Red Crag Stage. The entrapped southern forms were unable to survive in the colder waters of the North Sea; and at the close of the Red Crag Stage half of them had disappeared, while an increasing number of northern forms took their place.

The influx of northern forms and corresponding disappearance of the southern were accelerated by the gradual approach of the Arctic cold, which culminated in the Pleistocene.

As the polar ice crept southward, more and more of the southern forms succumbed to the increasing cold, and at the close of the Norwich Crag there was not a survivor left. Thereafter, only northern forms inhabited the North Sea.

The land flora of the Newer Pliocene was less affected by the increasing cold than the more delicately organised marine fauna, and at the close of the period still possessed the aspect of a temperate climate.

The *Lenham Beds* occur as a number of small patches on the North Downs between Maidstone and Folkestone at heights ranging from 500 to 600 feet above the sea. They contain some species found in the Miocene, among them being *Pleurotoma Jouaneti*, *Terebra acuminata*, and *Arca diluvii*.

The *Coralline Crag* is only known in South-East Suffolk, where it is well exposed in the neighbourhood of Aldeburgh and Orford. It consists mainly of fragments of polyzoans, molluscs, sea-urchins, and fish teeth, and may be regarded as a raised shell-bank. At its base, at Sutton, there is a phosphatic nodule bed with fossils derived from the London Clay and Jurassic rocks. This bed also contains an assortment of different rocks, such as flints, granite, quartzite, quartz, sandstones, etc. The rounded blocks of brown sandstone are locally called *box-stones*, and from these the whole deposit has received the name box-stones. It is regarded as the oldest Pliocene.[1]

The *Red Crag* consists of sands frequently current-bedded, and shells usually broken. The sands and shells are stained a reddish-brown colour with peroxide of iron, hence the name *Red Crag*. Among the southern forms in this bed are *Cerithium trilineatum*, *Nassa limata*, and *Turritella incrassata* (Plate LXII. fig. 3), and among the northern, *Natica occlusa*, *Pleurotoma pyramidalis*, *Cardium grœnlandicum*, *Astarte Basteroti* (Plate LXII. fig. 8).

The *Norwich Crag* is a shelly sand and gravel deposit of fluvio-marine origin. A considerable proportion of the shells are freshwater. This stage is specially noted for the large number of mammalian bones which occur in a pebbly bed at its base. The mammals include representatives of the horse, mastodon, and elephant.

Among the characteristic boreal molluscs are *Astarte borealis* (Plate LXV. fig. 5) and *Nucula Cobboldiæ* (Plate LXV. fig. 4).

The *Chillesford Beds* in different places rest on the Norwich, Red, and Coralline Crags. They consist mainly of finely laminated micaceous clays

[1] H. T. Osborne White in "The British Isles" (*Handbuch der regionalen Geologie*, iii. 1), p. 277, 1917.

and sands. Among the numerous species of molluscs are *Cardium edule, Tellina calcaria, Mya truncata, Mactra ovalis, Nucula Cobboldiæ.*

The *Weybourn Crag* is a marine shelly deposit which contains *Astarte borealis, Mya arenaria, Saxicava arctica, Littorina littorea, Buccinum undatum, Neptunea antiqua,* and also the Lamellibranch *Tellina baltica,* which is unknown in older beds.

The *Cromer Forest Bed Series* is well developed in the Cromer Cliffs on the north coast of Norfolk. It comprises three distinct groups of beds—

Cromer Forest Bed Series	4. *Leda (Yoldia) myalis* Bed (marine).
	3. Upper Freshwater Bed.
	2. Forest Bed (estuarine).
	1. Lower Freshwater Bed.

The plant beds contain the remains of many forest trees, almost all of which are still living in Norfolk. All the marine molluscs are found in the Weybourn Crag. They include the extinct species *Tellina obliqua* and *Nucula Cobboldiæ.*

The vertebrates are exceedingly abundant and comprise numerous fishes (perch, cod, pike, sturgeon, etc.), reptiles, and birds (eagle, owl, cormorant, wild goose, wild duck, etc.). The marine mammals include whales, seals, and walrus. The ungulates are represented by the elephant, rhinoceros, hippopotamus, horse, bison, and wild boar; and the carnivores by the hyæna, wolf, dog, fox, otter, and marten.

Excluding the bat, the total species of land mammals is forty-five, as compared with twenty-nine living species. And of thirty large land mammals only three are now living in Britain, and only six survive elsewhere.

The *Leda myalis Bed*, a current-bedded, sandy, marine loam containing a few marine shells of boreal aspect, among which *Leda myalis, Tellina baltica,* and *Astarte borealis* are common, is now regarded as Pleistocene.

It is the same with the *Arctic Freshwater Bed*, which follows the *Leda myalis Bed* conformably. It contains the Arctic willow, *Salix polaris,* and the Arctic Birch, *Betula nana,* which indicate a mean temperature 20° Fahr. lower than the present mean temperature, sufficiently cold to allow glaciers to form on the mountains, and allow the sea to be frozen over in the winter months.

Belgium.—The Pliocene deposits across the Channel are a continuation of those in the east coast of England. The Older Pliocene deposits consist of shelly sands, and rest unconformably on the Miocene and older rocks. The fossils are mostly those that characterise the Coralline Crag and older Pliocene of England.

France.—In South France the Pliocene deposits have been raised to a height of 1150 feet above the sea. They consist chiefly of shelly sands and marly clays with bands of conglomerate. The three main divisions are as follows:—

3. Arnusian	Stage—	Freshwater, with volcanic tuffs.
2. Astian	,,	Fluviatile, lacustrine, and marine.
1. Plaisancian	,,	Marine.

Italy.—The Pliocene of Italy and Sicily are more fully developed than elsewhere in Europe. They occupy large tracts in Central and Southern Italy, forming low hills on both flanks of the Apennines; hence the name *Sub-Apennine Series* frequently applied to the Italian Pliocene.

In Sicily they cover about half the area of the island, and rise to a height

of 4000 feet above the sea. The volcanic activity which piled up Etna to its present gigantic size began in the Pliocene, the first eruptions being submarine. Since then the island and surrounding sea-floor have been steadily rising. The marine benches that contour round the north and east sides of the island are conclusive evidence of uplift in quite recent times.

The fauna is rich in molluscs and mammals, most of them related to forms found in the Pliocene of England.

Vienna Basin.—The Pliocene beds of this basin follow the Miocene quite conformably. They are usually called the *Congerian Stage* from the abundance of the Lamellibranch *Congeria subglobosa* or the *Pontian Series.* The deposits consist of brackish-water clays followed by fluviatile drifts.

The clays are estuarine and contain a rich assemblage of molluscs and mammalian remains. The overlying fluviatile drifts also contain mammalian remains.

The *Congerian Stage* was apparently deposited in a gulf that became detached from the sea, forming an inland basin like the present Caspian depression; and, like the Caspian Sea, it gradually freshened by the inflow of streams and rivers.

India.—The uplift of the Himalayas and the mountains of Baluchistan and Burma culminated in the late Miocene, consequently there are no marine Pliocene deposits in these regions. But along the foot of the Himalayas there remained a chain of salt-water basins and shallow lagoons, in which a thick series of deposits was laid down during the Pliocene Period. These beds consist principally of fluviatile sands, clays, and conglomerates, and constitute what is widely known as the *Siwalik System,* which is extensively developed in the Punjab, Baluchistan, Burma, and Assam. In Burma the Siwalik System is represented by the *Irawadi Beds.*

The sediments of this system were deposited by the streams and rivers flowing into the enclosed basins, their mode of formation in some respects resembling that of the *Flysch* deposits.

The variable salinity of the waters of these detached basins was unfavourable for the development of a prolific or vigorous organic life, the remains of which are consequently scanty. The molluscs are mostly living species; but the chief interest of the Siwalik System lies in the extraordinary number of fossil vertebrates which it contains. The mammals include many apes, the elephant and mastodon, numerous ungulates and carnivores. Fishes, reptiles, and birds are also well represented.

The living mammals include the elephant, horse, and bear.

North America.—Marine Pliocene beds play an unimportant part in the geological structure of the North American continent. They are sparingly developed along the Atlantic and Gulf coasts, occurring as isolated patches that are probably the remnants of a continuous sheet. The strata dip seaward under the accumulations of later date.

The bulk of the Pliocene deposits are lacustrine and fluviatile drifts that have accumulated in inland lake-basins.

The *Lafayette Series,* which consists of a series of sands, clays, and silts, is extensively developed between the Appalachians and the Atlantic, whence it sweeps around the Atlantic border to the Mexican Gulf coastal region. It spreads over a large tract in the lower Mississippi Basin and stretches into the coastal plains of Texas. Altogether this series covers an area exceeding 200,000 square miles.

The beds rest unconformably on the eroded surfaces of the Miocene and older rocks, and seldom rise to a height exceeding 200 feet above the sea.

The thickness of the sediments seldom exceeds 50 feet, and is usually less than 30 feet, but in a few places it reaches 200 feet.

This remarkable and widespread maritime formation contains no marine fossils, and the remains of land animals and plants are rare. Hence its age —Pliocene or Quaternary—is still uncertain. Though obviously of terrestrial origin, its mode of formation is still obscure.

Australia.—The gold-bearing drifts of Victoria and New South Wales that lie buried under sheets of basaltic lava range in age from Miocene to Pliocene. These buried *deep-leads* frequently contain lignite beds, and the trunks, branches, and leaves of trees, also freshwater shells and the remains of extinct marsupials, some of which attained a gigantic size. The most remarkable of these primitive mammals are the *Diprotodon*, the tapir-like *Nothotherium*, a giant kangaroo, a marsupial lion, and a marsupial hyæna.

In the late Pliocene or Pleistocene drifts there also occur the remains of some gigantic flightless birds related to the emu. Among these are *Dromornis australis* and *Genyornis newtoni*, both from Lake Callabonna, Queensland.

Besides the fossil land animals found in the *deep-leads*, the remains of many extinct animals occur throughout Australia in caves, river and lake drifts, peat-bogs, dune-rock, and other superficial deposits that suggest a Pleistocene rather than Pliocene age. The Darling Downs and Condamine River drifts in Queensland, the Wellington Caves in New South Wales, the Mount Macedon Caves in Victoria, and the Mammoth Cave in Western Australia, have yielded many genera and species. Tasmania has not yielded many examples, but the complete skeleton of *Nothotherium tasmanicum* found in a peat deposit at Mowbray Swamp in the north-west corner of the island is a proof of the former land-connection with Australia.

New Zealand.—Marine deposits of Pliocene age cover a wide tract in the North Island, where they rise as a gentle sloping plane from sea-level to a height of 3000 feet above the sea. They rest conformably on the Miocene strata, but overlap these and spread on to older rocks. Their uplift, like that of the Pliocene of Sicily, was connected with the volcanic outbursts that piled up the gigantic volcanoes Ruapehu and Tongariro, both situated in the centre of a great dome of elevation, from which the Tertiary strata dip towards the sea on the west, south, and east.

The molluscous fauna is related to that in the surrounding seas.

The marine Pliocene of New Zealand are mainly developed in the Hawke Bay and Wellington divisions of the North Island. Altogether they comprise a thickness of 2000 feet of clays, sandy beds, conglomerates, and shelly limestones. They constitute the Wanganuian System, the main subdivisions of which are—

	South Island.	North Island.
Pliocene	Absent.	Shakespeare-Cliffian.
	Absent.	Kai-iwian.
	Absent.	Nukumaruian.
	Waitotaran.	Waitotaran.
Miocene	Awamoan.	Patean or Awamoan.

CHAPTER XXXIV.

QUATERNARY SYSTEM,[1] PLEISTOCENE AND RECENT.

Pleistocene or Glacial Period.

THIS period covers the interval between the close of the Pliocene and the advent of Recent time. Its downward limit is not always very sharply defined from the Pliocene, and passing upward it merges imperceptibly into the Recent.

The duration of this period has been variously estimated at from scores of thousands to hundreds of thousands of years, which is a good reason for saying that we possess no sufficient data to enable us to form even an approximate estimate. Whatever its length expressed in years may be, it is generally agreed that the Pleistocene represents a shorter interval of geological time than the Pliocene or other Cainozoic periods.

The time that has elapsed since the close of the Glacial Period is estimated at from 10,000 to 50,000 years, the former number being the more trustworthy.

During the Pliocene, the Alps, Carpathians, Himalayas, and other great chains attained their full height, and at the close of that period the Earth finally assumed its present form. Since that date there have been no great earth-movements except those caused by local volcanic disturbances, but, as in past ages, the various processes of denudation have been unceasingly wearing away and modifying the surface of the dry land.

Pleistocene Glaciation.—The dominant feature of this period was the phenomenal increase of cold in both hemispheres, which permitted an extraordinary invasion of the temperate latitudes by gigantic ice-sheets moving down from the higher latitudes, and allowed glaciers to accumulate in regions where permanent ice did not formerly exist.

A vast ice-sheet radiated from the mountains of Scandinavia and spread over the whole of Northern Europe. It extended from the Ural Mountains to the Atlantic Ocean, and reached as far south as Central Germany and the basins of the Russian rivers draining into the Black Sea. This gigantic sheet bridged the Baltic Sea and filled the North Sea basin, whence it flowed southward as far as the English Channel. Its southmost limit in Europe was about 50° N. latitude.

At the same time enormous glaciers radiated from the Alps and spread over the foothills and neighbouring plains. The Pyrenees, Carpathians, and Caucasus were likewise considerably glaciated.

The whole of Scotland and practically the whole of Ireland were covered with ice, and in England the invading sheets reached as far as the basin of the Thames.

The magnitude of the Pleistocene glaciation was even greater in North

[1] Pleistocene+Recent=Post-Pliocene=Quaternary, when the geological record was divided into Primary, Secondary, Tertiary, and Quaternary eras.

America than in Europe. Glacial drifts were spread over the United States as far south as 37° N. latitude, or 13° further south than in Europe.

In South America and New Zealand the glaciers reached sea-level in 39° S. latitude, and in the Antarctic Continent the extent of the Barrier Ice-sheet was vastly greater than at present.

The trend of the researches in glaciology is to show that Europe and America were not glaciated by an invasion of the polar ice-cap, but by the accumulation of vast masses of ice in certain regions situated in lower latitudes. In Europe the centre of dispersion is placed in Northern Scandinavia; and in North America, in Canada along the sixtieth parallel of latitude. The evidences of regional glaciation are not sufficiently conclusive for general acceptance, and, after all, may be deceptive; and perhaps too much weight has been attached to the apparent absence of glaciation in Southern Siberia, and to the radial dispersion of the Scandinavian ice-sheet.

At each independent local centre of glaciation the ice-cap will naturally flow outward in all directions from the gathering ground independently of the surface configuration. In the case of valley glaciers the direction of flow will always be determined by the trend of the valley-walls.

In Scotland the local ice-cap radiated north, east, south, and west. It flowed north and east till it became engulfed in the superior mass of the southward-flowing Scandinavian ice-sheet.

Similarly the Scandinavian land-ice radiated outward towards all the cardinal points of the compass, and there is no evidence to show that it did not meet and merge into the advancing polar ice-sheet.

The great glaciation of North and North-West Europe may have been directly due to the existence of the superior gathering ground in Scandinavia. But there is no present evidence to show that the existence of the Scandinavian ice-sheet was independent or dependent of an advance of the polar ice-cap.

In North America the Pleistocene ice-cap covered Greenland and the whole of the northern portion of the continent, with perhaps the exception of North-West Alaska, as to which the evidence is too scanty for final pronouncement. The centres of accumulation and dispersion of the land-ice were localised in certain regions from which the confluent ice-sheets radiated in all directions.

The extreme cold which characterised the older Pleistocene did not come on suddenly. On the contrary, the effects of boreal cold began to be manifest as far back as the Middle Pliocene. The wholesale migration of Arctic forms into the East Anglian waters in the Newer Pliocene shows that the Scandinavian region was already in the grip of the ice-cap, and the advent of the boreal flora as contained in the Arctic Freshwater Bed denotes that the refrigeration was approaching a climax. After this stage, the cold continued to increase until the glaciation culminated about the Middle Pleistocene.

Subdivisions.—Some writers have maintained that as many as five or six distinct epochs of cold are represented in the Pleistocene, this view being based mainly on the occurrence of local intercalations of sand, gravel, clay, and peaty beds with mammalian and other remains in the Boulder-Clay of different countries. It is now recognised that these intercalations indicate little more than seasonal variations in the limits and thickness of the ice-sheets, such as now affect the Scandinavian, Alaskan, and New Zealand glaciers. Clement Reed [1] has shown that some of the peat-beds supposed to be interglacial contain the seeds of introduced and cultivated plants, and hence cannot be of the age claimed for them.

It is almost certain that the advance and retreat of the northern ice was

[1] *Geol. Mag.*, 1895, p. 217.

sufficiently slow to permit forests to flourish and peat-bogs to accumulate on the drift-covered lands close to the edge of the ice. During a temporary advance of the ice, the forests might well be covered over by fluvio-glacial sands, gravels, and morainic débris.

Three principal stages of glaciation may be distinguished in the Glacial Period, and they pass imperceptibly into one another. They are the *Advancing Stage*, the *Maximum Stage*, and the *Retreating Stage*.

The Ice Age in temperate latitudes began and ended in local glaciers which became confluent during the maximum refrigeration.

The *Advancing Stage* is characterised by the gathering of local glaciers—the outposts of the advancing northern ice. The *Maximum Stage* is distinguished by ice-sheets of great magnitude, and the *Retreating Stage* by local glaciers that cover the retreat of the main sheet and finally disappear or shrink back among the deep mountain valleys. Thus outside the polar regions we have—

Glacial Period:
3. Retreating Stage = Local glaciers.
2. Maximum Stage = Confluent glaciers and ice-sheets.
1. Advancing Stage = Local glaciers.

In the *Advancing Stage* the glaciers that already existed in the Alpine chains began to advance and grow in thickness. At the same time the seasonal snows on the lower ranges became permanent, and glaciers appeared where none existed before. A wintry boreal aspect now took possession of the land, and the Arctic plants and animals slowly retreated southward before the advancing ice, always keeping within the limits of climatic conditions corresponding to their natural habitat.

With the increasing refrigeration, the glaciers grew in size till they filled up the valleys and basins in which they lay.

In the *Maximum Stage* the advancing glaciers overflowed the valley-walls and deployed on to the foothills and plains, where they formed *piedmont* ice-sheets that slowly crept onwards till in some cases their terminal face was hundreds of miles from the centre of dispersion. In their onward course they passed over hill and dale, filled up lake-basins, and even bridged wide seas. In this stage the ice-sheets derived little or no rocky débris from projecting peaks or *nunataks*; nevertheless, they carried an immense load of soil, clay, sand, and broken rock scooped up from the floor over which they flowed. The conditions now resembled those prevailing in Greenland at the present time.

In the *Retreating* or *Waning Stage*, as the result of the gradual approach of milder climatic conditions, the ice-sheets began to shrink and retreat, and in time they disappeared from the coastal plains and foothills. Shrunken in thickness and no longer able to override the valley-walls, the ice now began its long retreat up the mountain valleys.

When half-way back to the Alpine chain, the glaciers in the temperate regions halted and entrenched themselves behind piles of morainic débris. Behind these temporary fortresses they held their ground for a time, and on two or more occasions made desperate sallies beyond the barriers. Beaten back by the increasing and relentless warmth, they soon began the final retreat which ended in the disappearance of all but those which took their rise in the higher Alpine chains.

Polyglacialism.—There is a widespread opinion that there occurred more than one stage of Pleistocene glaciation in different regions of the Earth.

The occurrence, between sheets of drift, of beds of peat and clays with fossil leaves and wood, and of sands, with bones of many kinds of mammals,

has been regarded as a sign of a considerable retreat of the glaciers or even of their complete disappearance. This view seems to be supported by the alternation, in the Quaternary deposits, of groups of plants and animals living in different climates. One set is of northern origin and of cold habitat, while the following one is from the south and of mild climes. In North America the cold climate assemblages have among other forms reindeer, caribou, musk-oxen, moose, woolly mammoths, and walrus, while those of the warm climates have lions, sabre-tooth tigers, peccaries, tapirs, camels, llamas, horses, great sloths, *Elephas imperator* and *E. Columbi*, and the manatee. It is assumed that there were extensive migrations of animals from one part of the continent to another, as the climatic conditions changed. The times with moderate climate are called interglacial, and the cold ones glacial. In the latter musk-oxen spread into Utah and Oklahoma, and the mammoth lived south of the Ohio and Potomac rivers, while in interglacial times the mastodon ranged into Alaska and the manatee occurred in New Jersey.

Many geologists hold that during the Pleistocene the temperature varied more than once between cold and warmer climates. As to the number of these alternations there is no unanimity, some recognising three, others four, five, and even six glaciations, with corresponding interglacial epochs.

The Pleistocene deposits of North America are divided by Chamberlin and Salisbury into five time stages, but the evidence that these are separate and distinct is not convincing.

In Europe Penck and Brückner have divided the glacial deposits of the Alps into four groups, regarded as representing about the same number of glacial stages. The deposits are unsorted, fluvio-glacial gravels appearing in terraces in the plateau that borders the northern margin of the Alps. They occur along the tributary rivers of the Danube. The names of the glacial stages are taken from these rivers : Günz, Mindel, Riss, Würm.

In the vast territories covered by Pleistocene drifts in Northern Germany the Geological Survey of Prussia arranges the glacial deposits in three groups assigned to three glacial stages, called—

3. Weichsel glacial time.
2. Saale glacial time.
1. Elster glacial time.

In Germany, as in Great Britain, there are geologists who do not support the theory of polyglacialism.

Glacial Evidences.—Glaciers and ice-sheets leave behind them a twofold evidence of their former existence. By their erosive effects, they modify the configuration of the surfaces over which they pass, and they leave behind them piles of detrital material of various kinds.

A glacier or moving sheet of ice by the sheer weight of its mass removes all the irregularities of the surfaces over which it flows, with the result that the contours become rounded and smooth. Rough rocky hills lying in the path of the moving ice are worn down into rounded, hummocky, or whale-backed mounds or *roches moutonnées*, and the surfaces of the rocks are scored, scratched, and polished by the cutting effect of the blocks embedded in the bottom of the ice. Protruding spurs are truncated, and benches, steps, and broad platforms frequently excavated on the mountain slopes. Prominent peaks and ridges that are overridden by a stream of ice are worn down into rounded domes.

A region that has suffered intense glaciation usually presents smooth-flowing contours and soft outlines.

The detrital material consists mainly of fluvio-glacial drifts, terminal morainic piles often arranged in crescent-shaped mounds, and ground-moraines called *till* or *boulder-clay*.

But regions that have been intensely glaciated do not always show conspicuous evidences of ice-erosion and other glacial phenomena. There is proof of widespread glaciation in Alaska, yet extensive areas of land are now bare of glacial detritus, and the evidences of ice-erosion have been almost completely removed by later fluvial denudation. In Spitzbergen, which suffered prolonged glaciation, there are extensive tracts that are bare of the usual criteria of glaciation. According to Lamplugh [1] there is more drift in an equivalent area of the British Islands than is now visible in Spitzbergen. This is also true of the region lying to the north of Lake Superior. Here we find thousands of square miles of intensely glaciated country devoid of all glacial detritus, and tens of thousands of square miles of equally ice-shorn country with only a scattered boulder drift that seldom hides the surface of the beautifully glaciated hummocks.

Fluvio-Glacial Drifts.—Glaciers and ice-sheets in all the stages of their existence are drained by streams and rivers which pick up and re-sort the detritus discharged at the terminal edge, and spread it out as a wide sheet or apron of rudely-sorted, water-worn, and semi-angular drift in front of the ice-sheet. In this way glacial valley-trains are formed (fig. 29).

Older Drifts.—The drifts formed during the advancing stage are obviously the oldest. In many places they were cut up by the advancing ice, carried forward, and again deposited at the terminal face.

It is obvious that, where the ice-stream travelled far from its gathering ground, the drifts and detritus laid down in the earlier stages of the advance may have been re-sorted over and over again before the ice-flow reached its furthest limit. The constituent particles and blocks by the continuous grinding and attrition of the moving ice and the wear and tear of the glacial streams and rivers become smaller and more rounded. Hence, in a long journey only the harder rocks are able to survive in the form of sand and gravel. The softer rocks are reduced to the condition of silts and muds, much of which is carried to the sea by the glacial streams.

Morainic Mounds.—These are formed at the halting-places both during the advance and retreat. The morainic mounds formed during the advance are overrun by the ice when it resumes its forward movement, and are thereby broken up and re-deposited in a re-sorted form. The morainic mounds formed during the retreat remain intact except where they have been attacked by the glacial streams and rivers issuing from the ice-face.

Terminal moraines are formed at the utmost limits reached by the ice, provided the retreat does not begin as soon as this limit is reached.

Older Moraines.—When the ice-sheet halted for a time at the utmost limits reached by it, the rocky load of débris transported under, in, and on the ice is piled up as a terminal moraine. Such moraines are of great antiquity, and are obviously older than those formed during the retreat. Hence they are called *Older Moraines* to distinguish them from the *Newer Moraines* formed in the valleys and old alpine lake-basins during the later stages of valley glaciation.

Boulder-Clays or Ground-Moraines.—During the retreat the rocky débris entangled in the ice is shed as a sheet over the ground from which the ice has disappeared. In places the deposit may be thick, in others thin or altogether absent according to the distribution of the material in the ice. It may be spread over valley, hill-top, and slope alike, but is usually thickest

[1] G. W. Lamplugh, *Proc. Yorks. Geol. Soc.*, vol. xvii. p. 240.

in the hollows as the tendency of the newly fallen material is to gravitate downwards.

At certain places the ground-moraine may be attacked and re-sorted by the glacial streams issuing from the ice, and spread out as an apron of drift and silt in front of the terminal edge. In this way a boulder-clay may pass gradually, or may be suddenly, into rudely stratified sand and gravel drifts.

There is abundant evidence that arboreal vegetation and land animals followed up the retreating Pleistocene ice pretty closely, and in this situation their remains would be liable to be covered over with glacial débris during minor advances of the ice arising from fluctuations in the climatic conditions.

Thickness of Ice-Sheets.—The thickness of the Scottish ice-sheet during the period of maximum refrigeration as determined by the height at which ice-worn rocks are met with has been estimated at 5000 feet; of the Scandinavian, up to 13,000 feet; of the New Zealand, 7000 feet; and of the North American, from 7000 to 15,000 feet.

Local Glaciation.

British Isles.—During the period of maximum glaciation the whole of Scotland was covered with a sheet of land-ice which radiated outwards from the Highlands in all directions. On the east side the Scottish ice spread some distance over the sea and repelled the invading Scandinavian ice which now occupied the North Sea, and on the west it covered all the Western Isles and stretched an unknown distance into the Atlantic. The portion covering the Western Lowlands crossed the Irish Sea and invaded the north-east corner of Ireland.

Passing southward it encountered the Welsh buttress with its ice-cap, and was diverted into two main streams, the eastern stream flowing southward through the Lancashire depression between the Pennine Chain and Highlands of Wales, the western or main stream pursuing its course down the Irish Sea between South-East Ireland and Wales.

The Irish Sea was so completely filled that the ice rode over the summit of Snaefell, the highest point in the Isle of Man, which is 2034 feet above the sea.

The Lancashire ice-stream flowed as far south as the basin of the Severn, and covered the greater portion of Lancashire, Cheshire, and Shropshire.

The western stream passed through St. George's Channel, chafed against the rocky coasts of Pembroke, and advanced so far south that the ice-face peeped into the Bristol Channel.

The local glaciers of Ireland formed a sheet of land-ice which covered the whole of the island, with the exception of Counties Antrim and Down, and some adjacent areas in the north-east corner already occupied by the Scottish ice, and perhaps a fringe along the south coast.

The Welsh glaciers formed a small but compact wedge of ice lying between the two main branches of the Scottish ice. On the west side they descended into Cardigan Bay, and fended off the Scottish ice; on the south sent long tongues of ice into the Bristol Channel; and on the east descended into the basin of the Severn.

The Scandinavian ice filled the North Sea and reached as far south as the English Channel, but it was unable to encroach on the Scottish mainland on account of the superior pressure of the land-ice descending from the Highlands.

In England, where the land-ice was thinner and its pressure less, the Scandinavian ice was able to invade the coastal fringe from North Durham to the Humber. South of the Humber it spread over a large tract, covering

practically the whole of Lincolnshire lying east of the Trent, the whole of the counties of Norfolk, Stafford, and Cambridge, and portions of the adjoining Midlands, as far south as the north side of the Thames Valley.

Local glaciers held possession of the Cheviot Hills on the border, and the highlands of Cumberland and Westmorland.

The former extent of the local glaciers and invading Scottish and Scandinavian ice is shown by the distribution of the rocky débris and erratics scattered over the land, and by the direction of the ice-striated rock-surfaces.

The main struggle for supremacy between the Scottish and Scandinavian ice-sheets seems to have centred about the north-east corner of England, and partly as a result of this struggle, and partly as the result of the check the Scottish ice received from the Cheviot barrier, and the resistance of Northumberland and Westmorland glaciers, there appears to have remained a neutral ground—a kind of no-man's-land—embracing a large portion of the North, East, and West Ridings of Yorkshire, and the greater part of Nottinghamshire lying west of the Trent, where no ice intruded.

Glacial Deposits.—The character of the glacial deposits varies from place to place, and is largely dependent on the character of the rocks and the local conditions of glaciation.

Generally the glacial deposits of a region may be classified as (*a*) those formed during the Advancing Stage ; (*b*) those that accumulated at the utmost limits reached by the ice ; and (*c*) those formed during the Retreating Stage.

The pre-glacial deposits are mainly fluvio-glacial drifts, and from their nature are mostly composed of local detritus.

The deposits formed during the maximum refrigeration are mainly terminal moraines which may contain erratics mingled with the local débris, and wide-spreading aprons and trains of fluvio-glacial drift formed by the streams issuing from the ice-face.

The glacial deposits of the Retreating Stage are mainly boulder-clays intercalated with fluvio-glacial drifts. It is in this stage that *eskers* of sand and drift are formed in subglacial channels and ice-tunnels.

There is no general agreement as to the succession of the different glacial deposits scattered throughout the British Isles, and much diversity of opinion exists as to how some of them were formed. And the difficulty is complicated by the presence of organic remains in some of the deposits. But perhaps this difficulty is not so great as it appears. The ancient belief that the advance of the northern ice necessarily involved the destruction of all animal and plant life in its neighbourhood is now known to be fallacious. Recent research has shown that forests may flourish and peat-bogs grow on the moraines and valley-trains of a glacier up to the edge of the ice. Forests may even establish themselves on the clays and rocky débris carried on the back of a glacier.

In New Zealand the famous Franz Josef Glacier is embowered in a luxurious evergreen forest at a height of 670 feet above the sea, in 43° S. latitude.

It is certain that where forests could grow, the woolly mammoth and woolly rhinoceros, the Arctic reindeer, the moose, and bear would find a genial habitat.

Forests and peat-bogs in front of a glacier are always liable to be covered over by fluvio-glacial drifts or overwhelmed by ice during a temporary advance of the ice.

The rapid advance of the Malaspina Glacier, in Alaska, which followed the great earthquakes at Yakutat Bay in 1899, caused a wholesale destruction of the forests lying in front of the ice-face.

The *till* or Boulder-Clay of Scotland is spread over the lowlands and mountain valleys, and usually rests on ice-worn rocks. It consists mainly of

stiff, unstratified clay mingled with semi-angular blocks of stone, and varies from 0 to 100 feet thick.

In some places near the coast the till overlies beds containing Arctic shells, and in other places it is intercalated with sand, gravel, laminated clay, and layers of peaty material with plant remains, and the teeth and bones of the mammoth and reindeer.

The Boulder-Clay of England is well developed in East Anglia and the counties around the Wash, where four local subdivisions are recognised—

4. The Chalky Boulder-Clay.
3. Mid-glacial Drift.
2. The Contorted Drift.
1. Cromer Till.

The *Cromer Till* consists mainly of stiff glacial clays with striated fragments of chalk, flint, and an assortment of Jurassic rocks, Carboniferous limestones, and various igneous and metamorphic rocks. Some of the boulders are clearly erratics from the north. The rhomb-porphyry is believed to have come from the neighbourhood of Christiania, and also the boulders of the rock called *Laurvikite*.

The *Contorted Drift*, which is well exposed in the Cromer Cliffs on the north coast of Norfolk, is a yellowish-brown loam, with irregular layers of gravel, sand, and clay. It contains many boulders and some enormous blocks of chalk. This deposit is rudely stratified, and on the north coast sharply contorted, a feature resulting probably from ice-thrust.

The *Mid-glacial Sands* contain marine shells and ostracod crustaceans of a northern type.

The *Chalky Boulder-Clay* rests on the Contorted Drift, but also extends far beyond the limits of that deposit, being found as far south as the Thames Basin. Generally it does not differ much from the Cromer Till, but contains fewer Scandinavian boulders.

The Chalky Boulder-Clay is so named from the prevailing colour and the presence of numerous fragments and blocks of chalk. It passes north of the Wash into Lincolnshire and East Yorkshire. The infra-glacial beds at Speeton contain land and marine shells and the remains of mammals, among them being *Elephas antiquus*, *Rhinoceros*, and *Hippopotamus*.

In East Anglia Scandinavian blocks are comparatively common, in East Yorkshire they are rare, and further north in Scotland they are practically unknown, the pressure of the Scottish land-ice having thrust the Scandinavian North Sea ice away from the mainland.

Most of the erratics in the Boulder-Clay of England are from Scotland and North England. For the most part they are igneous rocks of limited outcrop and distinctive character, and hence easily traced to their original source.

The Scottish ice flowing down the Irish Sea transported blocks of the riebeckite-granite from its source at Ailsa Craig, on the Firth of Clyde, to the Isle of Man, Anglesey, and St. David's Head in Pembrokeshire.

Among other erratics carried southward are the grey granites of Galloway, the pink granophyre and granites of the Lake District, and the andesites of the Borrowdale Volcanic Series. Boulders of the famous Shap granite were carried from the Lake District eastward into Yorkshire by way of Teesdale.

In Lancashire, Cheshire, and north coast of Wales, the Boulder-Clay is irregularly intercalated with shelly sands and gravels that do not occur in a constant horizon. The undisturbed condition of certain sandy beds under the Lancashire Drift might be due to the sand being completely frozen in the

Pleistocene age. A. H. Brooks has reported that the drifts of Alaska are even now permanently frozen to a depth exceeding 300 feet. In Eastern Siberia bore-holes have shown the drifts to be permanently frozen to a depth of 1200 feet.

At Macclesfield, in Cheshire, these shelly deposits occur at a height of 1200 feet above the sea, and are held by some writers to be a proof of submergence. The shells, however, are often striated, and comprise a mixture of deep and shallow water forms, and though embedded in clay they are frequently filled with sand. The shells are always associated with erratics transported across an arm of the sea, and were doubtless scooped up from the sea-floor and transported in the body of the ice to their present situations.

Vast numbers of shells, mostly unbroken, were discovered by Lamplugh[1] in the terminal moraine of the Sefström Glacier, Spitzbergen, after it had crossed an arm of the sea. This occurrence is of great significance. It is corroborated by similar evidence from Alaska and South Victoria Land; and shows how readily marine material can be lifted from the sea-floor and transported by an advancing sheet of land-ice. The perfect condition of the sea-shells would lead us to suppose that the marine sediments in which they occur were frozen at the time they were scooped up by the ice-sheet.

The Lancashire branch of the Scottish ice-sheet from the Irish Sea reaches as far south as Wolverhampton, in South Staffordshire, where it dropped a vast number of erratic boulders. The southern limits of the ice-sheet in the Thames Basin are not marked by a terminal moraine, which would indicate that the ice did not halt when it reached these limits, but began the northerly retreat almost at once, scattering an irregular sheet of boulder-clay in its wake.

The city of York is built on the terminal moraine of one of the tongues of ice that protruded from the Scottish ice-sheet.

Continental Europe.

The Scandinavian ice-sheet passed over Finland and spread into North-East Russia, reaching as far as the Ural Mountains. It bridged the Baltic Sea, advanced southward across the great Germanic Plain, and even reached the northern slopes of the Harz Mountains and Riesengebirge, where it scattered Scandinavian erratics of gneiss, granite, etc , up to a height of almost 1500 feet above the sea.

The maximum thickness of this gigantic ice-sheet is estimated to have been not less than 13,000 feet.

Glacial detritus is scattered over almost the whole of Northern Europe. It varies from 0 to 670 feet thick, and generally decreases in thickness from north to south.

The deposits exhibit many local variations, which frequently take place with startling suddenness. But as in other glaciated regions, the succession is difficult to unravel.

The lowest deposits are fluvio-glacial drifts composed of well-worn sands and gravels formed by the streams and rivers that issued from the front of the advancing ice-sheet. These *Pre-glacial Drifts*, as they are sometimes called, are followed by boulder-clays, which consist of stiff clays, with numerous blocks of stone only slightly rounded and frequently scratched, grooved, and polished. The lower portion of these glacial clays is a bluish-grey colour

[1] G. W. Lamplugh, "Shelly Moraine of Sefström Glacier," *Proc. Yorks. Geol. Soc.*, vol. xvii. pp. 231–236.

which weathers to a yellowish-brown near the surface. Furthermore, as in England and Scotland, the boulder-clays are intercalated with irregular deposits of fluvio-glacial drift composed of sand, gravel, and silt, often rudely stratified. In these so-called *Inter-glacial Drifts* are found the teeth and bones of mammals, peaty matter, and plant remains. Among the mammals are the mammoth, rhinoceros, giant elk, reindeer, ox, bear, etc., which are common in the neighbourhood of Berlin.

These animals probably followed the retreating ice-sheet, and frequented the broad reed and moss-covered plains spread out in front of the ice. There they lived and died in great numbers. When the ice-sheet made minor advances, the drift with their remains became covered over with a sheet of boulder-clay.

Along the Baltic fringe the glacial clays contain many marine molluscs, among which *Leda* (*Yoldia*) *arctica*, *Cyprina islandica*, and *Corbula gibba* are prominent.

The northern glaciation was accompanied by a great extension of the Alpine glaciers, and glaciers occupied the slopes and deep valleys of the Pyrenees, Vosges, Black Forest, Riesengebirge, Urals, and Caucasus, where permanent ice-fields no longer exist.

The Pleistocene was a period of great fluviatile activity. Fluvio-glacial and fluviatile drifts were spread over the valley-floors to a great depth, far in advance of the limits reached by the ice, forming high-level flood-plains.

These drifts were deposited during both the advance and retreat of the ice, and hence range in age from the earliest to the latest Pleistocene. The rivers, in the process of excavating their present channels, have in many places left strips or remnants of these drifts at different levels along the valley-walls. Obviously the lowest terraces are composed of the oldest drifts, and the highest terraces of the youngest.

The *loess*, which covers a large portion of Northern Europe, and extends from the English Channel to Galicia, Hungary, and Russia, is probably the wind-borne flood-silt of the rivers draining the front of the ice-sheet, mingled with wind-blown desert-dust from the vast areas of boulder-clay, from which the ice-sheet had just retreated. It spreads over hill and dale, and varies from 0 to 80 feet thick.

The loess is an excessively fine, yellowish, powdery, unbedded sand, and in an unweathered state is calcareous. When exposed in natural cliffs or artificial cuttings, it shows a tendency to assume a vertical cleavage. By weathering the carbonates of lime and magnesia are destroyed and the loess becomes a brown-coloured loam.

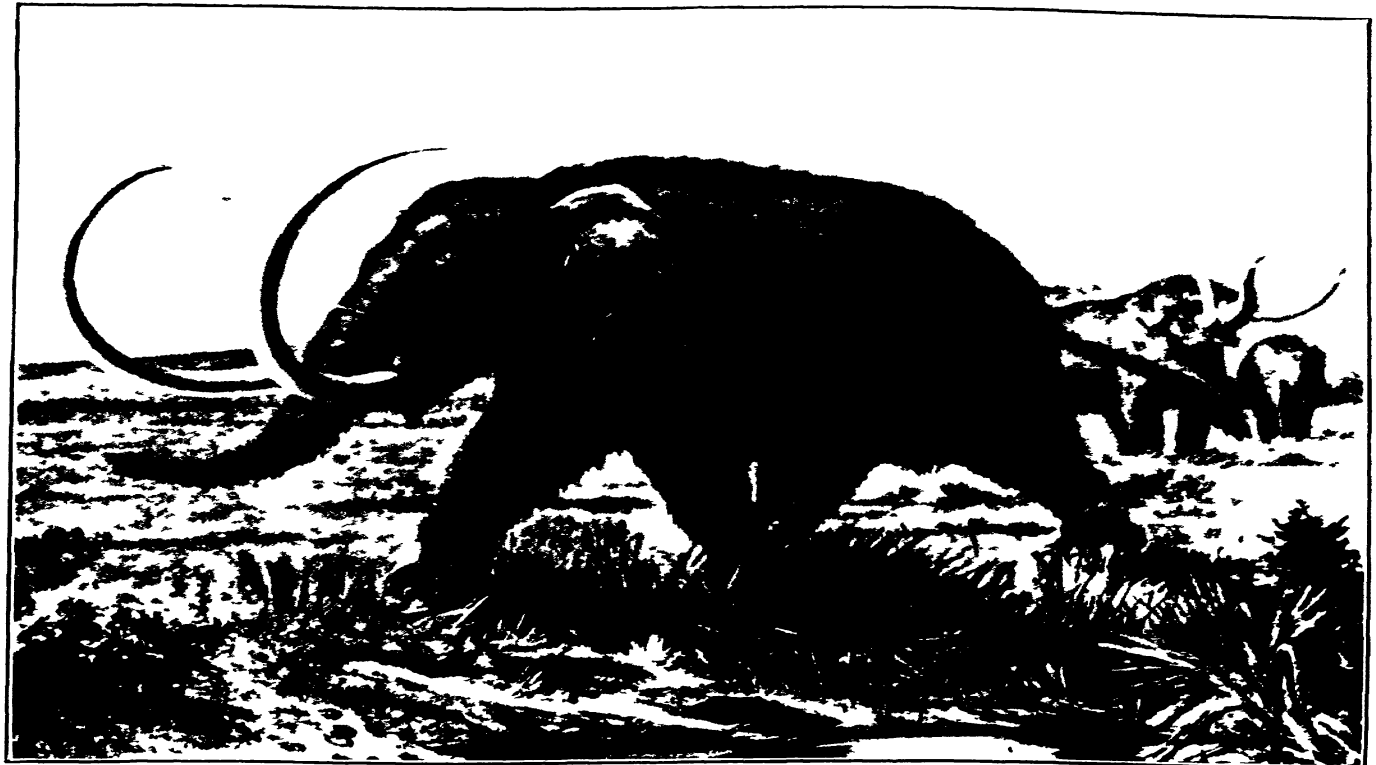
Among the land shells found in this remarkable silt are *Helix hispida*, *Succinea oblonga*, and *Pupa muscorum*, which are characteristic and widely spread. The remains of the mammoth and rhinoceros are not uncommon.

Northern Asia.—Of the Pleistocene glaciation of this region very little is known. It is, however, quite certain that the glaciers of the Himalayas extended far beyond their present limits, but how far has not yet been ascertained.

The great piles of morainic material in the valley of the Kotchurla River show that the ancient glaciers of the Altai Mountains at one time spread northwards many hundreds of miles from their gathering ground. A few small glaciers still cling to the mountain slopes at the sources of the Mushtuaire River in the Obi Basin. Some of the valley-glaciers in alpine Turkestan are of gigantic size.

The taigas and tundras of Northern Siberia are covered with a vast sheet

SECTION OF GLACIAL DRIFT. NORTH-EAST PART OF NEWARK, NEW JERSEY. (N.J. Geol. Survey.)



MASTODON AMERICANUS. (After Chamberlin and Salisbury.)

of fluvio-glacial drift, and as in Northern Europe and North America, the mammoth occupied a prominent place in the fossil fauna.

The mammoth lived in extraordinary numbers along the northern border of that region, where the well-preserved bodies are found in the permanently frozen soil.

In Pleistocene deposits the constant companion of the mammoth, and like it protected with a coat of woolly hair, is the boreal rhinoceros (*Rhinoceros antiquitatis*). With these also occur the bones of the horse (*Equus fossilis*), and in Southern Europe *Hippopotamus major*, the last scarcely distinguishable from the living *H. amphibius*.

North America.—The Pleistocene glaciation of this continent was even greater and more intense than in Northern Europe.

There is evidence that the northern half of the continent from the Atlantic to the Pacific was covered with a continuous ice-sheet, which stretched northward toward the polar regions and spread southward into relatively low latitudes.

The confluent ice-sheets are believed to have radiated from four main gathering grounds, namely, the Greenlandian, Labradorian, Keewatin, and Cordilleran, the last three situated on the mainland between the parallels 52° and 55° N. latitude. The Labradorian centre lay about 1800 miles east of the Keewatin or Central gathering ground, and the Cordilleran about 1000 miles west of the Keewatin. The ice-streams from these centres, though so far apart, united as they radiated outward into a gigantic sheet, which altogether covered an area of about 4,000,000 square miles.

The Cordilleran or Western ice-sheet crept southward to 47° N. latitude, and the Labradorian to 37° or 1600 miles from the centre of dispersion. From the great glacial centres the confluent ice-sheets spread northward, and probably joined the advancing polar ice.

The glacial and fluvio-glacial drifts spread over the land by the Pleistocene ice-sheet vary from 0 to 500 feet thick, and erratics have been found over 1000 miles away from the parent rock in the north. The greatest thickness of drift is usually found towards the southern limits reached by the ice-sheet. In the profoundly glaciated region lying between Lake Superior and Hudson Bay, glacial drifts are conspicuously absent over vast areas.

The mammalian remains in the glacial drifts include the mammoth and mastodon (Plate LXIV.), but the rhinoceros, hippopotamus, and hyæna, so common in the drifts of Northern Europe, are absent in North America.

Fluvio-glacial drifts are conspicuous in the Western States, particularly in the Great Basin lying between the Rocky Mountains and Sierra Nevada Chain. In this region there exists several large lake-basins that have been partially or completely filled by glacial drifts. The most notable of these glacial lakes are Lake Bonneville, of which the Great Salt Lake is the remnant, and Lake Lahontan. The drifts in the former are mingled with a considerable quantity of volcanic ash, the product of eruptions within the lake area.

Southern Hemisphere.

The evidences of intense and widespread glaciation are plentiful in South America, Falkland Islands, New Zealand, New South Wales, Tasmania, and Antarctic Continent.

In 1872 Agassiz,[1] the veteran glaciologist, announced the discovery of evidence that South America in the Pleistocene Period was covered with a

[1] A. Agassiz, *Am. Jour. Sc.*, 1872, vol. iv. p. 135.

continuous ice-sheet extending from the Atlantic to the Pacific as far north as 37° S. latitude, or 1400 miles north of Cape Horn. But long prior to this, Darwin had called attention to the thick masses of boulder-clay and other criteria of glaciation in Tierra del Fuego.

The advance of the southern ice was accompanied by a corresponding development of Alpine glaciers in the Central Andes. In Bolivia glacial deposits cover both sides of the Andes, and are particularly well displayed along the western slopes, where they are piled up on the foothills to a depth of many thousand feet. In many places the streams draining the existing glaciers have excavated profound gorges through these accumulations. At La Paz the glacial drifts are intercalated with thick deposits of volcanic tuff and breccia. Obviously the Pleistocene glaciers of this region attained gigantic proportions.

The Pleistocene fauna of South America is distinguished by the presence of gigantic sloths and armadillos, which were indigenous to that region.

In **New South Wales** Mount Kosciusko was covered with a cap of glacier-ice, and in Tasmania glaciers of considerable magnitude descended almost to sea-level.

Owing to its isolation Australia followed its own lines of development. The vertebrate fauna still consists exclusively of marsupials and monotremes, the last represented by the singular *Ornithorhynchus* provided with a duck bill and webbed feet.

In **New Zealand,** with its massive Alpine Chain as a gathering ground, the confluent glaciers descended to the sea-coast all round the South Island, and covered the greater portion of the surface with an almost continuous ice-sheet, through which only the higher peaks projected as gigantic *nunataks.*

In this region, where the evidences of intense and prolonged glaciation are remarkably well preserved, there is nothing to indicate more than one period of Pleistocene refrigeration, which, as in Europe, may be divided into three phases or stages, each characterised by its peculiar glacial accumulations.

In the *Advancing Stage* the glaciers descended the valleys and filled up the great lake-basins lying at the foot of the Alpine Chain with fluvio-glacial drifts. The pre-glacial drifts were afterwards cut up and deeply eroded by the advancing glaciers, which continued their seaward journey till they emerged on the foothills and coastal plains.

On the west coast the confluent glaciers extended far out to sea ; but on the east coast they halted at the present coast-line, where the confluent glaciers formed a piedmont ice-sheet, on the terminal front of which there were piled up vast morainic accumulations. Of these the Taieri Moraine in East Otago is perhaps the largest in existence. It is 35 miles long, and varies from a few hundred yards to three miles wide, covering a coastal range of hills which rises in places to a height of over 1000 feet above the sea.

The great Marlborough Moraine, which occurs 300 miles further north, can be traced along the east coast for 30 miles up to latitude 41° 30′ S.

In the North Island of New Zealand the existing Ruapehu glacier sent along streams of ice down the neighbouring valleys.

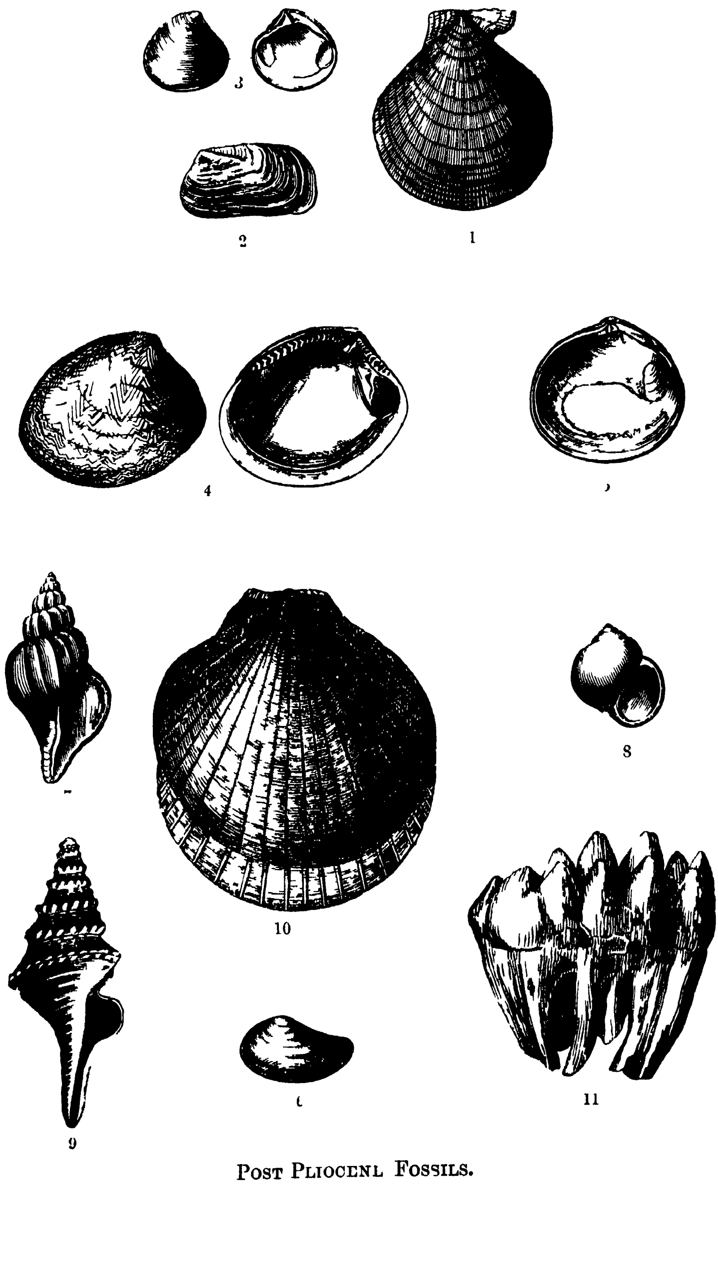
When the glaciers in their retreat had reached the inland basins sheltered by the coastal ranges, they halted and for a time entrenched themselves behind barriers of morainic material which they piled up to a great height. On two occasions they made minor advances of ten or twelve miles, and then began the final retreat which ended in the extermination of all but the larger glaciers, the remains of which still occupy the Alpine Chain.

During the retreat vast quantities of fluvio-glacial drift were shot into the

PLATE LXV.

POST-PLIOCENE FOSSILS.

1. *Pecten islandicus* (Mull.). Clyde beds, etc., reduced.
2. *Saxicava rugosa* (Penn.). Clyde beds, etc.
3. *Astarte borealis* (Chem.). Glacial clays, half natural size.
4. *Nucula Cobboldia* (Sow.) Glacial and Mam. Crag.
5. *Tellina proxima* (F. & H.) *lata* (Gmelin).
6. *Leda oblonga* (Sow.) (*lanceolata*). Glacial beds and Arctic seas.
7. *Trophon clathratus* (Linn.). Glacial beds.
8. *Natica clausa* (Brod.). Glacial beds.
9. *Pleurotoma rotata* (Defr.). (Sub-Apennines.)
10. *Pecten pleuronectes* ?
11. Tooth of *Mastodon*, one-fourth natural size.



POST PLIOCENE FOSSILS.

inland basins, most of which were completely filled up. At the present day the filling up of the remaining lakes is proceeding with almost incredible rapidity.

The **Antarctic Continent** is covered with a vast polar ice-sheet from which gigantic glaciers descend to the sea all around the continent.

In South Victoria Land the confluent glaciers descend to sea-level and form the famous Ross piedmont ice-sheet which stretches northwards across the deep sea for hundreds of miles, its outer edge forming the well-known Great Ice Barrier first seen by Ross.

The gigantic glaciers, the phenomenal Ice Barrier, the ice-worn domes, and scattered erratics found on both sides of the continent, are sufficient to warrant the view expressed by Scott and others that the Antarctic glaciation of the Pleistocene must have been vastly greater than at present.

During the Glacial Period the Scandinavian ice-sheet extended across the North Sea many hundreds of miles, and the Antarctic ice-sheet still extends over the sea for 500 or 700 miles, notwithstanding that the maximum glaciation is now long past.

How far the ice extended northward during the Glacial Period is unknown. It seems not improbable that the ice-sheet from Graham's Land crossed the intervening sea to the Falkland Islands and met the land-ice which spread over the southern portion of South America. The ability of land-ice to spread over deep seas, so long denied, is now generally recognised by geologists.

Causes of Glacial Period.—Many hypotheses have been advanced to account for the Pleistocene refrigeration, but as yet no agreement has been arrived at, and the final solution seems as far off as ever. Among the more probable causes that have been suggested we have—

(1) Variations in the eccentricity of the Earth's orbit, as advanced by Croll.
(2) Wandering of the polar axis.
(3) Depletion of the carbonic acid in the atmosphere first suggested by Herbert Spencer and afterwards urged by Arrhenius.
(4) Climatic changes arising from Pliocene uplift of great chains.

It is now realised that powerful climatic changes may be caused by the elevation of land masses such as great mountain-chains, and that these meteorological changes may be accentuated by a redistribution of land and sea, causing a deflection of established sea-currents.

The present trend of investigation is to lay less stress on probable astronomical causes, and to devote more attention to the analysis of the effects of land-masses, air- and sea-currents, variations of precipitation, etc.

It is suggestive that the great mountain-building of the Carboniferous was followed by widespread glaciation in the Permian Period in both hemispheres.

Recent or Post-Glacial.

The end of the Pleistocene or Glacial Period is not very clearly defined, but is usually placed at the time when the ice-sheets retreated from the lowlands in temperate latitudes.

The Glacial Period can only be regarded as a past geological age in the latitudes from which ice-sheets have completely disappeared. Greenland is still in the Ice Age. The climatic conditions which now exist in that northern land are not unlike those prevailing in Northern and Central Europe during the period of greatest Pleistocene glaciation. Similarly the Antarctic region,

though now in the waning stage of glaciation, is still in the grip of a vast ice-sheet from which gigantic glaciers descend to the sea.

Deposits.—The deposits of the Recent Period include those now in process of formation, such as river silts, sands, and gravels; beach sands, muds, and gravels; desert sands, dust, and soils; growing peat-bogs; the detritus from recent volcanic eruptions; the shell-banks and coral reefs growing on the sea-coasts. They also comprise those lately formed, such as river flats, old fluviatile fans, peat-bogs, cave-deposits, sand-dunes, and raised beaches. The growth or formation of some sand-dunes, peat-bogs, and fans has been continuous from the close of the Pleistocene up till now.

Since the beginning of the Recent Period, the streams and rivers have cut their channels a few feet or a few yards deeper, and the sea has encroached on the land, or the land on the sea; but these changes are relatively insignificant.

Fauna and Flora.—The existing fauna and flora are more prolific and varied than at any other period of the Earth's history.

Foraminifera, which first appeared in the Cambrian, now attain their greatest development. Nummulites, which were so numerous and large in the Eocene and Oligocene, are still represented by one or two species found in subtropical waters.

Single corals are exceedingly numerous; and rock-building corals, which have played an important *rôle* as geological agents since the remotest times, still thrive as abundantly as ever in the warm clear waters of the tropical seas, and, as in former ages, are accompanied by sea-urchins and Nullipores in great numbers.

Crinoids, which attained their greatest development in the Silurian Period, now seem to be rare, but recent investigations have detected many genera and species.

Brachiopods, which dominated the marine faunas of some of the Palæozoic formations, have shown a steady but slow decline since the Silurian, and at the present day are represented by a mere handful of genera, among which we still have *Rhynchonella*, *Terebratula*, *Magellania*, *Crania*, *Discina*, and *Lingula*. The first and last three are forms of great antiquity. Although only a few genera survive, the individuals of some species exist in such vast numbers as to indicate a great reserve of latent vitality.

Molluscs are represented by hordes of Lamellibranchs, Gasteropods, and Cephalopods, the geographical distribution of which is now more than ever dependent on climatic conditions and environment.

The Cephalopods, with chambered shells so numerous in the Jurassic and Cretaceous periods, are poorly represented in the Cainozoic era. But we still have the *Nautilus*, the fragile Argonaut, and *Spirula*, the beautiful shell of which is sometimes cast up on sandy shores in thousands.

Cephalopods of the octopus and cuttle-fish kind are more plentiful than ever, the only fossil form of these of any importance being *Belemnites*, of which there were scores of species in the Middle and Upper Mesozoic.

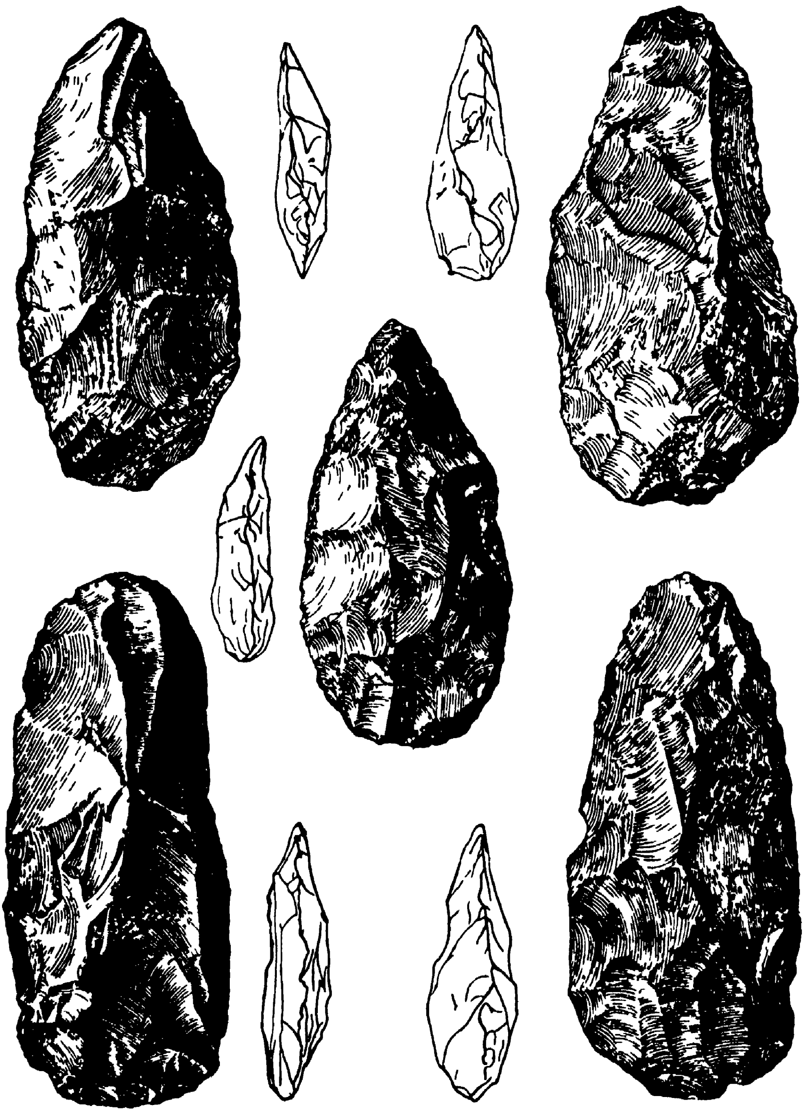
Crustaceans are still represented by a vast number of Ostracods, Cirripedes (barnacles, etc.), Isopods, and Decapods (lobsters, cray-fish, crabs).

Fishes, birds, and mammals now attain their greatest development.

The dominating figure among the mammals is man (*Homo sapiens*); hence the name *Age of Man*, sometimes applied to the Recent Period.

In the Australian Continent, on account of its isolation and persistence as a land-surface, the marsupial mammals and the primitive Eucalyptus vegetation still dominate the fauna and flora.

The plant remains discovered in Middle Cainozoic rocks in Greenland,



PALÆOLITHIC IMPLEMENTS. (After Holmes.)

Alaska, and Antarctic regions, supplemented by the abundant evidence provided in temperate and tropical countries, shows that nearly all plant families, except such specialised forms as the *Orchidaceæ* among the Monocotyledons, and the *Compositæ* and their allies among Dicotyledons, were at one time more widely distributed than at present.

Subdivisions.—The remains of man and traces of his handiwork have been found in drifts ascribed to the Pliocene Period, but the evidence has been challenged, and in every case the age of the deposits is open to doubt.

The presence of human remains or weapons in deposits of Glacial Age would tend to show that man already existed in Europe in the Glacial Period, and followed the ice as it retreated northward.

There are no unquestioned evidences of man in the glacial deposits of England; and since the land connection between Britain and the Continent was probably not broken till the late Pleistocene, it seems unlikely that he would venture into this region till the ice-sheet had disappeared for some time from the lowlands. It is almost certain that man would follow and not precede the vegetation and land-animals which followed close on the wake of the retreating ice.

The remains of man that mostly occur are the weapons and implements he fashioned and used; and as these show a progressive development of skill in their manufacture the nearer we approach our own time, they afford a means of dividing the Human Period into stages. The earliest weapons and implements were made of stone and bone; hence the earliest Human Period is called the *Stone Age*, which was successively followed by the *Bronze Age* and *Iron Age*.

(3) Iron Age.
(2) Bronze Age.
(1) Stone Age $\begin{cases} (b) \text{ Neolithic.} \\ (a) \text{ Palæolithic (Plate LXVI.).} \end{cases}$

In the *Palæolithic*[1] or *Old Stone Age* the weapons, tools, etc., of primitive man were roughly chipped from blocks of flint, obsidian, chert, quartzite, aphanite, and other fine-grained rocks, but in the *Neolithic*[2] or *New Stone Age* they were ground and polished with much skill and patience.

(*b*) Neolithic = New Stone Age = Well-finished implements.
(*a*) Palæolithic = Old Stone Age = Roughly fashioned implements.

The Palæolithic and Neolithic represent stages of cultural development rather than periods of time. Hence the Palæolithic of one region may overlap the Neolithic of another. At the advent of Europeans, the Australian aborigines were still in the Palæolithic stage of culture, and the Maori of New Zealand in the Neolithic. Neither of these isolated races was acquainted with the manufacture or working of metals.

In Continental Europe and England there are numerous caves in which relics of Palæolithic man are associated with the remains of large extinct mammals. In many cases the relics and animal remains are protected with a layer of calcareous stalagmite. This covering cannot always be regarded as an evidence of great antiquity, as calcareous sinters and stalagmitic deposits are known to accumulate with great rapidity in favourable situations. In the rock-shelters in the Waipara district in Canterbury, the bones of the sheep, introduced less than seventy years ago, have been found buried under an encrusting layer of calcareous stalagmite four inches thick.

[1] Gr. *palaios* = ancient, and *lithos* = a stone.
[2] Gr. *neos* = new, and *lithos*.

Most European naturalists of repute agree as to the existence of Pleistocene man. The skeletons of man himself, the stone implements, the occurrence of bones of Pleistocene animals broken to get at the marrow, the fine drawings of mammoths and other animals hunted by this man, and many other indications prove the existence of a Pleistocene man in Europe.

In 1856 an important discovery of human remains of a primitive type was made in a cave in the valley "Neanderthal" lying between Düsseldorf and Elberfeld. Since then the remains of more than 15 other men, women, and children of this race have been found in caves and rock-shelters at Spy in Belgium, Gibraltar, Krapina in Crotia, and other localities; and what are believed to be their implements are found scattered throughout Western Europe and eastwards into Poland, Crimea, and Asia Minor.

This race, called *Homo primigenius* or Mousterian man, was the first cave-dweller. The Neanderthal people were short, thick set, and strong, with a low, flattened forehead and a prominent bony brow. They knew how to kindle a fire and make good stone implements. Though belonging to another race, the Australian and Tasmanian natives are the nearest relatives of the Neanderthal folk.

The burial habits of primitive man must always be borne in mind when the remains of man and of extinct animals occur together. On his arrival in New Zealand, the ancient Maori found the bones of the gigantic moa in rock-shelters and caves, and widely scattered among the coastal and inland dunes. He fashioned implements of them, and buried heaps of the larger bones with his dead. Curiously shaped stones have always had a fascination for the aboriginal natives of Australia. He places them about his camping-grounds, and sometimes regards them as emblems of good and evil. Some of the earliest examples of the extinct marsupial *Diprotodon* were discovered at the native camping-grounds on the Darling Downs in Queensland.

We have no reason to believe that the primitive hunters of Europe were less inquisitive in respect of animal remains they may have found in caves, or on the banks of streams, or in slips, than the Maori or the blackfellow of Australia.

The evidence furnished by cave-deposits and river alluvia must always be subjected to critical examination before using it as the basis for far-reaching deductions as to the antiquity of man.

There is conclusive evidence that Palæolithic man was contemporary with several extinct mammals, which include the mammoth (*Elephas primigenius*), the woolly rhinoceros (*Rhinoceros tichorhinus*), the giant Irish elk with flattened horns (*Megaceros giganteus = hibernicus*), long-faced ox (*Bos primigenius*), hippopotamus (*Hippopotamus major*), the cave hyæna (*Hyæna spelæa*), and the cave bear (*Ursus spelæus*).

This association may mean either a considerable antiquity for man, or the existence of these animals up to a time not so very remote. The final solution of this problem has not yet been found.

A discovery that for a time was believed to have an important bearing on the antiquity of man was made by Eugene Dubois in a fossil-bearing stratum of drift on the left bank of the Solo, or Bergawan stream, near the centre of Java. The fossils included the human-like remains, *Pithecanthropus erectus*, consisting of the roof of a skull, a thigh bone, and two teeth, which were found associated with a rich fauna and flora. Of the mammalian fauna no less than 19 genera and 27 species were discovered, all of which are now extinct or greatly modified. But 87 per cent. of the Gasteropods found in the same bed are living species. Hence the drift with its remains cannot be older than Pleistocene. The human-like remains were at first supposed to supply the

missing-link connecting man and the anthropoid apes, but are now acknowledged to be those of an anthropoid ape closer related to man than any other existing or fossil ape.

Human remains were found in 1911 by the Yale Peruvian Expedition in the Cuzco Valley embedded in drifts under 75 feet of gravel. They were associated with the bones of several lower animals, and are believed to be of Pleistocene age.

In 1911 an important discovery of ancient human remains was made in a gravel pit near Piltdown Common, Fletching, Sussex. The gravel bed lies about 80 feet above the river Ouse, and less than a mile to the north of the existing stream. The deposit is about 4 feet thick, and consists mainly of water-worn fragments of Wealden ironstone and sandstone, with a few chert pebbles and a considerable proportion of water-worn flints derived from the Chalk of the South Downs. Portions of a human skull were found associated with a jaw of pronounced simian type, and the remains of an elephant, a mastodon, hippopotamus, and red deer, besides flint implements. The skull shows a high cranial development, but is believed by Professor Keith to belong to a man of greater antiquity than the *Neanderthal* flat-skulled man of Germany, or the *Spy* man of Belgium characterised by enormous brow-ridges. This view is supported by Dr. Smith Woodward, but has been traversed by Gerrit S. Miller who contends that the cranial portions of this famous skull are unequivocally human, while the lower jaw is as certainly that of a chimpanzee. Dr. W. K. Gregory throws the weight of his authority on the side of Miller.

In 1884 a human skull was found in the bed of a creek at Talgai, near Clifton, in the Darling Downs district of Queensland. The canine teeth are the largest of any human teeth so far discovered. Dr. A. Smith describes the Talgai man as belonging to an extremely primitive type of probably Pleistocene age. Unfortunately, no information has been preserved as to the mode of occurrence of this interesting skull. The Talgai discovery is important as showing the wide dispersal of man at the time of his first appearance in Europe.

In August 1921 an important discovery of human remains of a primitive type was made in Rhodesia by Mr. W. E. Barron, a mining graduate of Otago University. The remains were found in a cave in the Rhodesia Broken Hill Development Company's mine, 90 feet below the surface, and 60 feet below water-level. They were associated with the broken bones of the elephant, lion, leopard, rhinoceros, hippopotamus, antelope, and other small deer, many birds, and with rude stone and bone implements. The human remains included a nearly complete skull, a fragment of the upper jaw of another, a sacrum, a tibia, and two ends of a femur. The skull is in a remarkably good state of preservation, and, unlike the remains of primitive man found in Europe, is not in the least mineralised. It shows a close resemblance to the skull of the Neanderthal race from the caves of Belgium, France, and Gibraltar. The brain-case is typically modern, and its capacity well above the lower human limit. The massive brow-ridges, heavy face, and enormous palate give a more simian appearance than seen in Neanderthal man. The tibia and femur of *Homo rhodesiensis* are very different from the corresponding bones of the cave man of Europe. The tibia is long and slender, and essentially modern; and the extremities of the femur do not differ materially from those of a tall and robust modern man.

The Rhodesian man may prove to be the next grade after Neanderthal man in the ascending series.[1] This view would support the suggestion of Prof. Elliot Smith that the refinement of the face was probably the last step in the

[1] A. S. Woodward, *Nature*, Nov. 1921, pp. 371–372.

evolution of the human frame. The South African discovery is an evidence of the wide distribution of primitive man at the close of the Pleistocene.

Anthropologists have recognised a series of periods that are supposed to represent the cultural development of prehistoric man. These cultural periods are named after the localities, where the cultures are typically developed, *e.g.* Chelles, a town east of Paris, Seine-et-Marne, and Acheul, near Amiens, in France. They are characterised by specific forms of implements. The man of Chellean, Acheulian, and Mousterian cultural stages was *Homo primigenius* (Neanderthal races). The younger periods show the existence of a man of somatic characters which do not differ from those of recent man. The man of younger Palæolithic time, Aurignacean up to Azylian, is called the Cro-Magnon race.

NEOLITHIC PERIOD.

Palæolithic periods		Azylian. Magdalenian. Solutrean. Aurignacian.
	Older	Mousterian. Acheulian. Chellean.

These cultures belong in part to glacial, in part to intra-glacial times, *e.g.* the climate of the Chellean was mild and moist as shown by the wild growth of fig-trees and laurels. The extinct animals characteristic of this stage are *Elephas antiquus*, *Rhinoceros merkii*, the cave-bear, *Hippopotamus minor*, and the striped hyæna. The contemporary man belonged to the Neanderthal type.

Among the most prolific bone caves or *hyæna-dens* in England are the famous Kirkdale Cave, near Kirkby Moorside, in Yorkshire; Dream Cave in Derbyshire; Banwell Cave in the Mendip Hills; Kent's Hole, near Torquay; and Cefn, near Denbigh.

Caves rich in bones have been found in France, in Germany, in Austria, in Carniola and Hungary.

No Palæolithic remains are known in Scotland or the far north of England.

Nothing is known of man in North America during the Pleistocene.

In Britain Neolithic relics are found in sand-dunes, caves, peat-bogs, swamps, and in tumuli which are now known to be the tombs of Neolithic man. The associated fauna is quite distinct from that of the Palæolithic age. Most of the large mammals have become extinct, but the Irish elk, reindeer, and bear, which no longer survive in England, were present, together with the fauna of early historic times.

Raised beaches that contain many molluscs, all of them living forms, occur around all the continents, and may be observed on the shores of England, Scotland, Norway, Finland, France, Sicily, Italy, Egypt, East Africa, North Africa, Arabia, India, Malaysia, Australia, Tasmania, New Zealand, North and South America. The presence of these marine benches is an evidence of universal recession of the sea in quite recent times.

On some coasts, though the general movement of the land has been upward, there is evidence of local subsidence. In many lands there occur the remains of submerged, and partially submerged forests; and in many cases the trees are still standing in the positions in which they grew. The systematic study of coastal movements has not yet been undertaken, and in consequence it is

unknown whether the submergence arises from coastal sag or differential crustal movement.

SUMMARY.

From the earliest Cambrian when the first assemblage of organisms appeared, there has been a continuous procession of life, receiving accessions of new forms at each geological stage until it grew into the majestic stream which now floods the Earth in such amazing wealth of animal and vegetable life.

(1) The **Eocene Period** is specially characterised as the dawn of existing life, and it is sharply separated from the Cretaceous by the absence of the Cephalopods *Ammonites*, *Belemnites*, *Hamites*, *Turrilites*, *Baculites*, etc., and of the reptilians *Ichthyosaurus*, *Plesiosaurus*, and huge Dinosaurs.

The stratigraphical unconformity between the Cretaceous and Eocene is not strongly marked, and is often difficult to distinguish ; but the palæontological break is the greatest and most abrupt in the whole geological record.

The great Central Sea, *Tethys*, still stretched from the Atlantic to Further India. On its floor were accumulating thick deposits of Nummulitic Limestones, and on its margin piles of deltaic sands and muds of the *Flysch* facies of detrital deposits.

The volcanic forces which lay dormant during the whole Mesozoic era, but revived at the close of the Cretaceous, still continued to exhibit great activity in certain regions.

The dominating feature of the Eocene fauna is the advent of placental mammals, including ancestral forms of most of the large mammals of the present day.

The angiosperms or flowering plants which appeared in the Upper Cretaceous comprise the dominant vegetation in the Eocene forests, being represented by a great variety of Dicotyledons and Monocotyledons.

(2) The **Oligocene** is stratigraphically and palæontologically related to the Eocene, to which it properly belongs.

The Central Sea is still a feature of vast geographical and geological importance ; and on its northern shores the deposition of the deltaic sands and muds of the Flysch type continue to be deposited without interruption. At their outward limits the deltaic detritus is intercalated with the Nummulitic Limestone deposits formed on the floor of the deeper clearer waters of this great inland sea.

(3) The **Miocene** was a period of great geographical changes. It witnessed the uplift of the Pyrenees, Alps, Carpathians, Caucasus, and Himalayan Chains from the floor of the Central Sea, which thereby became reduced in size and broken up into large disconnected seas and inland salt-water lakes. It was at this time that the Mediterranean Sea, which is the last remnant of the great Tethys, was cut off from the Indian Ocean by the uplift of Syria, Asia Minor, Arabia, and Persia. Correctly speaking, the Mediterranean Sea is not simply a remnant of the Tethys, but has originated by later crustal subsidences, as shown by the interruptions of the mountain-chains within the regions now occupied by the different borders of the Mediterranean Sea.

The Miocene fauna and flora show an increasing relationship to the life of the present time. The mammals now include the *Mastodon*, true elephant, the huge *Dinotherium*, rhinoceros, hippopotamus, deer, whales, dolphins, etc.

(4) In the **Pliocene** the Alps, Himalayas, and other great chains attained their full height ; and the continents assumed their present forms.

Up till the middle of this period the climate of Northern Europe and North

evolution of the human frame. The South African discovery is an evidence of the wide distribution of primitive man at the close of the Pleistocene.

Anthropologists have recognised a series of periods that are supposed to represent the cultural development of prehistoric man. These cultural periods are named after the localities, where the cultures are typically developed, *e.g.* Chelles, a town east of Paris, Seine-et-Marne, and Acheul, near Amiens, in France. They are characterised by specific forms of implements. The man of Chellean, Acheulian, and Mousterian cultural stages was *Homo primigenius* (Neanderthal races). The younger periods show the existence of a man of somatic characters which do not differ from those of recent man. The man of younger Palæolithic time, Aurignacean up to Azylian, is called the Cro-Magnon race.

Neolithic Period.

Palæolithic periods	Younger	Azylian.
		Magdalenian.
		Solutrean.
		Aurignacian.
	Older	Mousterian.
		Acheulian.
		Chellean.

These cultures belong in part to glacial, in part to intra-glacial times, *e.g.* the climate of the Chellean was mild and moist as shown by the wild growth of fig-trees and laurels. The extinct animals characteristic of this stage are *Elephas antiquus*, *Rhinoceros merkii*, the cave-bear, *Hippopotamus minor*, and the striped hyæna. The contemporary man belonged to the Neanderthal type.

Among the most prolific bone caves or *hyæna-dens* in England are the famous Kirkdale Cave, near Kirkby Moorside, in Yorkshire; Dream Cave in Derbyshire; Banwell Cave in the Mendip Hills; Kent's Hole, near Torquay; and Cefn, near Denbigh.

Caves rich in bones have been found in France, in Germany, in Austria, in Carniola and Hungary.

No Palæolithic remains are known in Scotland or the far north of England.

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(4) In the **Pliocene** the Alps, Himalayas, and other great chains attained their full height ; and the continents assumed their present forms.

Up till the middle of this period the climate of Northern Europe and North

America was tropical or subtropical, but thereafter the character of the fauna and flora shows the approach, first of temperate, then of sub-Arctic cold. This gradual increase of cold was heralded by the southern migration of boreal forms into the temperate zones, both in Northern Europe and North America, and the migration of the southern forms into more congenial latitudes.

The fauna and flora of the Pliocene had already assumed a modern appearance, and 90 per cent. of the marine molluscs are living forms.

(5) The increasing cold culminated in the Pleistocene or Glacial Period, also called the Great Ice Age. In the early Pleistocene Northern Europe and North America were invaded by ice-sheets. In Europe the ice-sheet radiated outwards in all directions from the highlands of Scandinavia, and at the same time the Alpine glaciers crept down their valleys to the foothills and plains.

The Scandinavian ice-sheet bridged the Baltic Sea and filled up the North Sea as far south as the English Channel. The land-ice radiating from the Scottish Highlands flowed into the North Sea and fended the Scandinavian ice from the mainland; but in England the Scandinavian ice rasped the north-east coasts, and, flowing down the Wash gulf, overflowed East Anglia and the adjoining counties. Wherever it touched land it left a trail of Scandinavian erratics.

The Scottish land-ice flowed southward into England as far as York; and on the west coast filled the Irish Sea, which it descended till abreast of the Bristol Channel. It surged over the highest peaks in the Isle of Man, 3000 feet above sea-level; and sent a huge stream through the Lancashire Plain into Central England and basin of the Severn. The division of the Scottish ice on the west coast was due to the resistance offered by the Welsh mountains and their cap of land-ice.

The Pleistocene Period is divided into three stages, namely, the *Advancing Stage*, *Maximum Stage*, and *Retreating Stage*. That is, the Ice Age began and ended in local glaciers, which became confluent during the maximum stage of refrigeration.

The Advancing Stage was characterised by the deposition of vast deposits of fluvio-glacial drifts formed in front of the descending Alpine glaciers and advancing northern ice-sheet.

At the extreme limits reached by the ice during the period of maximum refrigeration, at the place where the ice-edge halted, there was frequently piled up high mounds and ridges of morainic material and widespreading valley-trains.

During the retreat, the ice scattered a sheet of boulder-clay or ground-moraine in its wake, forming a deposit that spread over hill and dale. Where the ice-face was drained by glacial streams or rivers, the boulder-clays were partially re-sorted and associated with fluvio-glacial drifts that frequently contain the remains of large extinct mammals. During minor advances of the ice, these drifts were sometimes covered over with morainic detritus, and thus became intercalated in the ground-moraines.

Throughout the retreat, fluvio-glacial drifts were continually deposited in front of the ice-edge, forming what are called the *Newer Glacial Drifts* to distinguish them from the *Older Glacial Drifts* formed during the advancing stage.

(6) The **Recent Period** is specially characterised by the advent of Man, whose relics are found in caves, drifts, and peat-bogs associated with the remains of some large extinct mammals, such as the woolly mammoth, woolly rhinoceros, great Irish elk, cave-hyæna, and cave-bear.

The Recent Period is divided into three main stages, namely—

3. Iron Age.
2. Bronze Age.
1. Stone Age.

The *Stone Age* is subdivided into two sub-stages, the Palæolithic and Neolithic. These are cultural rather than time divisions; though it must be understood that in a region in the continuous occupation of the same race, the palæozoic will always precede the Neolithic.

The *Palæolithic* was the age of rough, rudely fashioned implements, and the *Neolithic* the age of well-finished and polished implements.

Raised beaches occur around the coasts of all the great continents and islands, and indicate a general recession of the sea in comparatively recent times. But the existence of submerged forests in some places would indicate a recent downward movement that may be purely local, as arising from coastal sag, or more general as the result of differential movement.

CHAPTER XXXV.

DEVELOPMENT OF SURFACE FEATURES.

THE development of surface forms is mainly dependent (*a*) on the character and arrangement of the rocks, and (*b*) on the climatic conditions. Of these the last is perhaps the more important.

When we view broadly the surface configuration of the Earth, we have no difficulty in distinguishing two outstanding types of surface form, namely—

I. *Arid Erosion* type.
II. *Pluvial Erosion* type.

Arid Erosion Type.—Arid erosion may be defined as the degradation of the land by subaerial agencies where the annual rainfall is less than 18 or 20 inches. Its effects are best seen where the rainfall is confined to a few months in the year.

Arid erosion acts uniformly on all the surfaces exposed to the action of the atmosphere, but, owing to the effects of desert winds and gravitation, it is more energetic on the prominent land-features than elsewhere. Hence its general effect is to reduce the whole surface of the land to a plateau or base-level of low relief. The plateau form of feature is typical of arid erosion in all continental areas.

Good examples of plateaux of arid erosion may be seen in the high veldt lands of South and Central Africa, in the desert regions of the Western States of North America, in the sandy wastes of Arabia, Central Asia, and Mongolia, and in the high undulating forest-covered interior of Australia.

In South and Western Australia the edge of the great plateau is buttressed by great descending spurs and ridges frequently surmounted by what appear to be prominent mountain-peaks. Hence, when viewed from the sea-border, the edge of the plateau presents the configuration of a mountain-chain. The same rugged outline and Alpine effect is seen on the edge of the high veldt-lands of the Orange Free State and Transvaal when viewed from the Natal border.

A peculiarity of arid and semi-arid regions is the circumstance that many of the boulders and fragments of stone lying on the surface have become coated on the outside with a bluish-black shining glaze or enamel, consisting of manganese and iron oxides, mostly the former. The stones usually glazed in this way are basic and semi-basic igneous rocks and greywackes ; and where such are abundant, the black stones impart a burnt aspect to the landscape. The exposed surfaces of siliceous cement stones, which consist of sands that have been cemented into a solid rock by the infiltration of siliceous waters, and of siliceous sinters frequently become glazed with a vitreous enamel of silica. The formation of these enamels is apparently the result of chemico-capillary action.

The characteristic colour of arid landscapes is a warm yellowish-red hue arising from the peroxidation of the iron contained in the rocks and the glare of the sun in a cloudless sky. Desert sands and dust are characteristically red, frequently brick-red

Pluvial Erosion Type.—The general tendency of rain, frost, and other subærial agencies of denudation is to degrade the whole surface of the land; but the erosive effects of rain, in the form of brooks, streams, and rivers, is to wear away the surface faster in one place than in another. The streams will naturally follow fractured and faulted zones rather than excavate channels through solid rock, and they will erode soft rock-formations faster than hard.

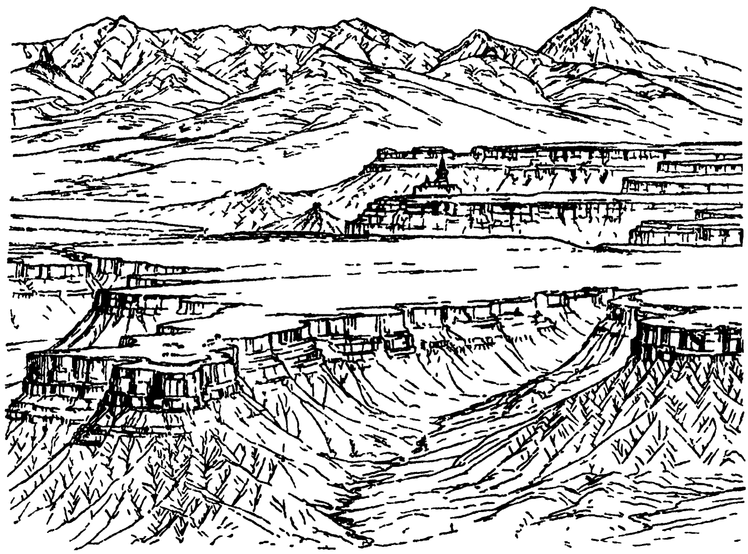


FIG. 221.—Showing erosion of plateaux in cretaceous rocks.
(C. E. Dutton, *U.S. Geol. Survey.*)

The general effect of this differential rate of denudation will be the gradual development of a variety of surface features, the form of which will be dependent on the character and arrangement of the rocks, the amount of the rainfall, and the velocity of the streams; and this last will be governed by the height of the land relatively to its base-level.

As erosion proceeds, the harder masses of rock will be left standing above the general level of the country, and they may form hills, ridges, or even mountains. In gently folded strata the harder bands of rock will form prominent lines of escarpment. Where gently-inclined strata are intersected by a strike-fault, the harder bands will form ridges with a steep descent into the fault-valley on the one side and a long gentle dip-slope on the other.

In a previous chapter we found that a rock-formation representing a cycle of deposition is usually closed by a bed of limestone In folded or faulted strata it is this calcareous member which usually forms the prominent escarpments or declivities of a landscape.

When a rock-formation contains a number of hard bands of limestone, conglomerate, or sandstone separated by clays, marls, or other soft rock, the outcrops of the hard bands not infrequently stand out as conspicuous escarp-

ments that can be traced by the eye for many miles as they contour around the ridges and mountain slopes (fig. 221).

Generally speaking, the denudation of formations composed of clays, marls, shales, chalk, or soft sandstones produces gentle slopes and smooth outlines, even when the beds are steeply inclined. Conversely, the denudation of hard rocks, and particularly of hard rocks alternating with soft, usually develops rugged outlines, more particularly where the strata are tilted at high angles. But a cycle of denudation has its stages of infancy, maturity, and old age; hence the character of the sculpturing as presented to the eye will depend on the progress made towards maturity or old age.

In a region occupied by a great thickness of mica-schist occurring in isoclinal folds, the rock in the infantile stage of erosion will be carved into V-shaped valleys and tent-shaped ridges. At a later stage the valleys will be widened and the ridges rounded; and in the decadent stage we shall get an area of gentle slopes and low relief, not distinguishable in configuration from the rolling downs composed of clays, marls, or shales.

As with mica-schist, so it is with slate or gneiss. Even a granite massif may form a bold mountain dominated with gigantic tors or a flat swampy moorland.

In regions that have been overrun with land-ice, the contours are softened and rounded. In Alpine valleys lakes may be formed by morainic barriers, and crescent-shaped piles of glacial débris scattered over the plains and foothills.

But pluvial denudation is not always destructive. When constructive, it is responsible for the development of many minor surface features, among which may be named the great alluvial plains and deltas that border the sea.

Mountains.

A mountain may be defined as a hill or ridge that rises conspicuously above the surrounding country. The term is in some respects a relative one, for the ridge that would form a conspicuous mountain on the plains of Prussia might sink into insignificance if placed among Alpine surroundings.

A mountain-chain is a narrow ridge or a succession of narrow ridges running more or less parallel with one another. The prominent peaks on a mountain-chain are often called mounts or mountains.

If we look at a physical map of the Earth, we shall find that (*a*) the continents are in general bordered with mountain-chains, and (*b*) that the highest border faces the larger ocean. The girdle of mountain-chains that encircles the Pacific ocean is a striking illustration of this type of continental fringe, and, moreover, it faces the greater ocean.

Origin of Mountains and Mountain-Chains.—Mountains and mountain-chains have originated in various ways, and, according to their origin, they may be divided into four classes—

(1) *Folded Mountains*, i.e. the *Alpine type.*
(2) *Volcanic Mountains.*
(3) *Plateau-Mountains.*
(4) *Residual Mountains.*

Folded Mountains.—This type includes all the great mountain-chains of the globe which are now known to consist of uplifted crustal folds; hence the origin of the distinctive name *Alpine* by which this type is sometimes not inappropriately designated.

To this type of folded chain belong the Andes, Rockies, Sierras, Appal-

HILLS CARVED FROM CRETACEOUS BEDS EAST OF BISBEE. (U. S. Geol. Survey.)

View is northward across Mule Gulch. The prominent white band is the upper member of the Mural limestone, forming the top of Mural Hill on the left and showing the dislocation due to the Mexican Canyon fault.

Representation of Willis' Experiments in the Artificial Production of Mountain Folds, with Layers of Wax of Different Colours (U.S. Geol. Survey.)

achians, Alps, Pyrenees, Carpathians, Urals, Himalayas, and New Zealand Alps.

The folding has been caused by lateral compression or thrust arising from the contraction of the Earth's crust. The most obvious result of compression is the shortening of the area occupied by the strata.

The geological investigations of Nicol, Lapworth, Peach, Horne, and others in the North-West Highlands of Scotland have proved conclusively that sharp folding is always accompanied by fracture and faulting; and sometimes by extraordinary horizontal shear, whereby overriding sheets of rock may be overthrust many miles from the place where they were formed. By a series of pressure experiments in 1888, Cadell obtained instructive imitations of the tectonics [1] of mountain-building, overthrust, and infolding of strata.

The forms of folded or tectonic mountains in their juvenile stages of existence are in a measure an expression of their structure. The ridges coincide with the anticlines, and the valleys with the synclines or downward folds. This juvenile structure is well exemplified in the Swiss Jura, which consists of parallel ridges, each dominated by an anticlinal fold, as shown in fig. 222.

With increasing age, and as the effects of denudation become greater and greater, the coincidence between folding and configuration becomes less and less, and finally disappears.

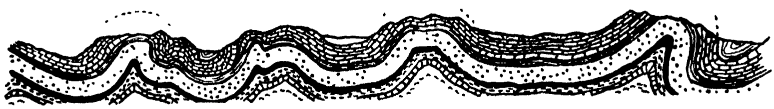


FIG. 222.—Section of Swiss Jura, from the Weissenstein in the S.E. to the basin of Delsberg in the N.W. (After Heim.)

In the Appalachian Mountains in Pennsylvania, denudation has progressed so far that the valleys follow the anticlines, while the ridges coincide with the synclines, which resist denudation more effectually than anticlines.

The mountains in time become remodelled by erosion; and the new configuration is determined by the character and arrangement of the rocks, and the climatic conditions. Such ancient folded mountains may therefore be so modified by erosion as to be difficult to distinguish from the type of mountains called *residual*. Many folded mountain-chains existed, of which only the worn-down stumps now remain. They have been truncated by the erosion in past geological ages, and partly buried under the detritus derived from their own destruction.

Volcanic Mountains.—These are hills or ridges piled up by the accumulation of lavas and other material ejected from a volcanic vent or fissure.

Volcanoes may rise from the floor of the sea, from a plain or plateau, or from the crest of an Alpine chain, as many do in the Andes of South America. They may occur as isolated mountains or in groups of mountains, each with its own crater, or in considerable chains.

Volcanoes of late Tertiary date usually retain their original form, modified perhaps to a small extent by recent fluviatile erosion, but the older piles of volcanic rocks have in most cases been so deeply eroded that they now present all the features and sculpturing of mountains formed by erosion.

Plateau-Mountains.—These are subordinate in extent and grandeur to the great Alpine chains composed of uplifted folds, but they present some features

[1] Gr. *tekton*=a builder.

of peculiar interest in connection with crustal movements. In Colorado and Utah, where plateau-mountains are well developed, four types of structure have been recognised by Powell and other members of the Geological Survey of the United States.

(1) *Uinta Structure.*—This type of structure is typically developed in the Uinta Mountains of Utah and Wyoming. It consists of two large monoclinal flexures bending in opposite directions, each with the downthrow on the external side, thus leaving a broad plateau-like mountain between them (fig. 222A, *A*). In some places the strata in the line of maximum flexure have given way, and here the bending stress has been relieved by fracturing, accompanied by profound faulting.

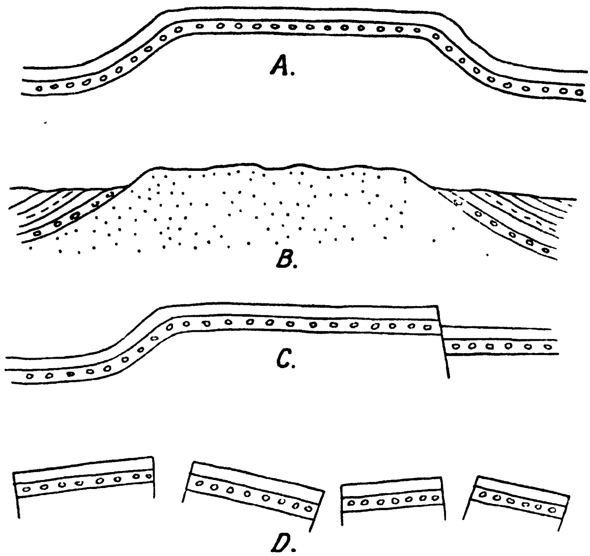


FIG. 222A.—Types of plateau-mountain structure.
(After Powell, modified by Rastall.)

(*A*) Uinta type. (*C*) Kaibab type.
(*B*) Park Plateau type. (*D*) Block-mountain type.

(2) The *Park Plateau Structure* is found in the Yellowstone Park region of Wyoming, where a thick series of Mesozoic rocks has been bent over a plateau-like complex of granites and gneisses, and afterward denuded, thereby leaving their truncated ends standing up at high angles against the flanks of the central mass of older rocks (fig. 222A, *B*).

(3) The *Kaibab Structure* is related to the Uinta structure, of which it is merely a modification. It consists of one dominant monoclinal flexure, and a powerful fault which dislocates the upraised horizontal strata (fig. 222A, *C*).

(4) *Block-Mountains.*—This type owes its origin to the displacement of large blocks, or segments, of the crust along the track of gigantic faults. Typical structures of this class are found in Colorado and Utah, and in Central Otago, New Zealand, all in arid plateau regions.

This structure is produced when a broad and lofty plateau, or elevated peneplain, is broken into blocks by profound faults. In the Great Basin region, lying between the Sierras and Rocky Mountains, the blocks are tilted at various angles (fig. 222A, *D*); but in Central Otago some have maintained a

nearly horizontal position, while others are tilted, but all are separated by wide rift-valleys or *graben*.

The New England area of New South Wales, according to Andrews, is a tilted, deeply dissected crustal block.

In the far north of Queensland, at the root of Cape Yorke Peninsula, the great inland plateau, as the writer has found, is a similar tilted block, sloping gently

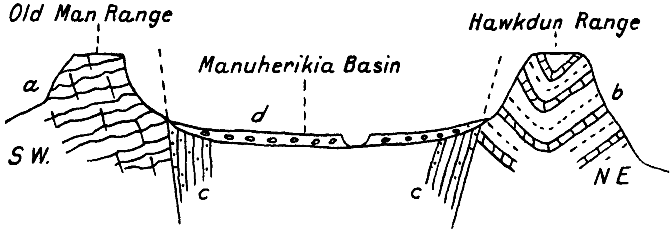


FIG. 223.—Showing block-mountains of Central Otago, N.Z.

(*a*) Mica-schist.
(*b*) Triassic sandstones and shales.
(*c*) Middle tertiary lacustrine beds.
(*d*) Pleistocene gravels.

towards the north-west. The rivers that drain this terrain rise near the east coast and traverse the surface of the plateau in shallow trenches. From this last we learn that the tilting, which uplifted the North Queensland block, is of comparatively recent date. The coastal edge of the plateau is frayed with the deep gorges of the streams that drain the eastern limits of this upland. These streams are antecedent, and excavated their present glen-like valleys during the progress of the uplift.

The coastal topography of North Queensland is suggestive of powerful

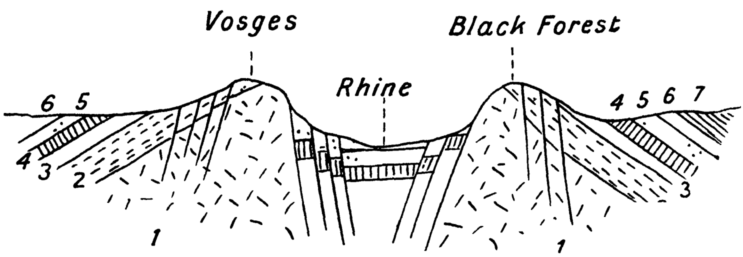


FIG. 223A.—Showing the Rhine flowing in a Rift-valley.

1, Granite. 2–7, Mesozoic rocks.

faulting, the course of the dislocation running parallel with the general trend of the mainland. The bearing that this faulting may have had on the growth of the Great Barrier Reef has still to be investigated. It may be found that the increase in sedimentation arising from the uplift of the land, and not subsidence, was primarily responsible for the outward growth of the reef to its present site.

Horsts.—For well-defined blocks that have remained as elevated masses while the areas around them have sunk, Suess has used the German term *horst*. Such fixed blocks are closely related to *block-mountains*. Typical examples are the mountains of the Vosges and Black Forest, which owe their existence to the subsidence of the segment which now forms the rift-valley of the Rhine. It is to be noted, that these horsts are not bounded by faults on their outer side (fig. 223A).

Large portions of Australia, of Central and South Africa, have been land

areas since the earliest times, and may be looked upon as forming horsts of continental dimensions. These immovable blocks are mostly composed of complex masses of crystalline rocks, and in a large measure they have controlled and directed the lateral crustal movements of younger Palæozoic and later times. They have formed the *thrust-blocks*, or anvils, against which the unaltered sedimentary formations have been crushed, folded, and sheared.

Similar unyielding blocks occur in the Alaskan and Laurentian regions; and on a smaller scale we have the crystalline block forming the substructure of Great Britain, with its protruding domes in the Southern Uplands and Northern Highlands of Scotland. Nearly antipodal to this there is the New

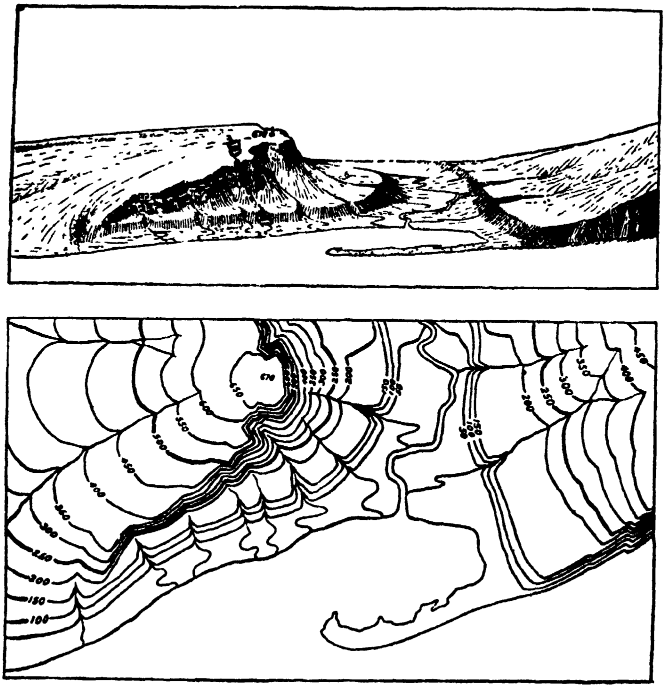


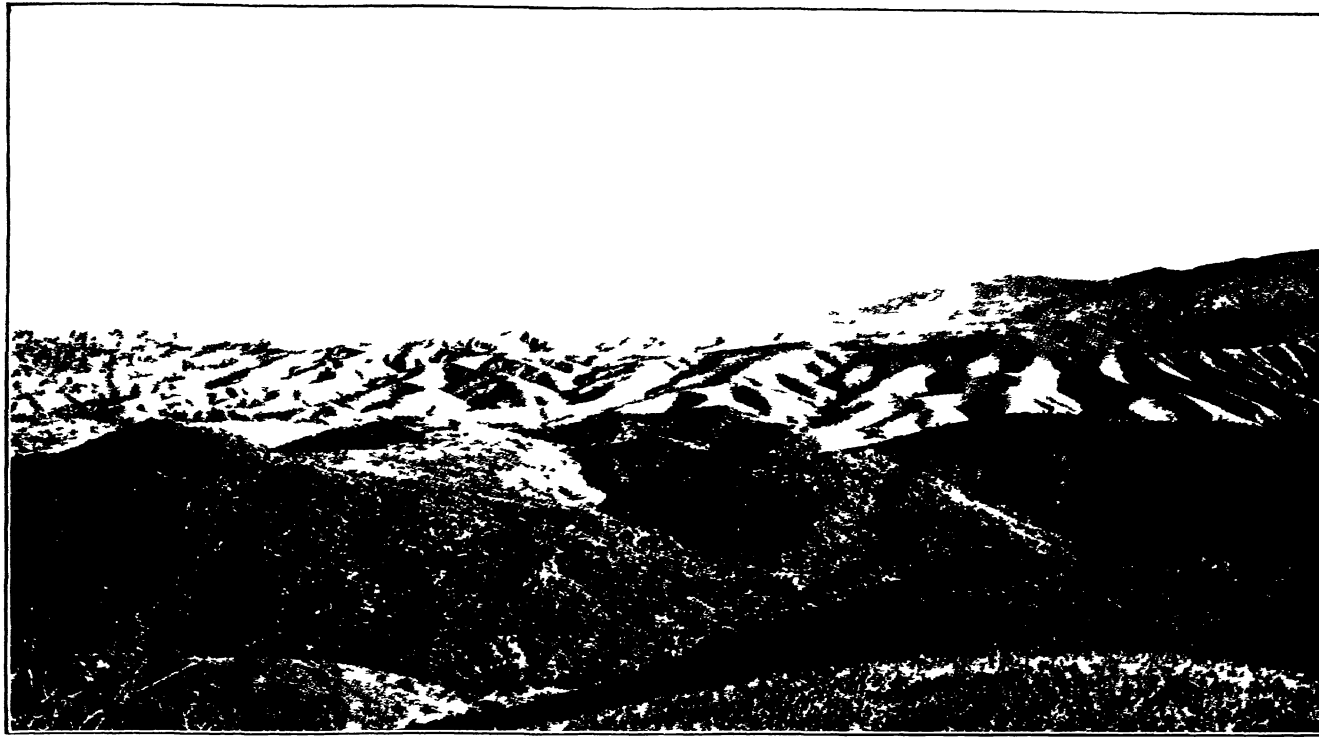
FIG. 224.—Sketch and corresponding contour map, *U.S. Geol. Surv.*

Zealand crystalline block, to the existence of which the distant Dominion owes its oceanic character.

Residual Mountains.—These are formed by the removal of the surrounding country by erosion. Residual mountains and ridges therefore owe their existence to their ability to resist denudation.

When a high plateau has been deeply dissected by the erosion of considerable streams and rivers, the portions that have escaped destruction may sometimes form a complex of ridges and mountains with narrow crests and projecting peaks. As a rule, residual mountains do not occur in continuous chains like the Alpine type, nor do they show any symmetrical arrangement. On the contrary, they usually occur as a tumble of isolated ridges and mountains.

The Highlands of North Scotland are a good example of mountains of the residual type. A study of their structure shows that they are merely the remnants of the ancient Caledonian plateau, that itself represented the stump of a still more ancient folded mountain system.



SHOWING EFFECTS OF SUBAERIAL EROSION IN ARID REGIONS (After Ransome U S Geol Survey)

Origin of Plateaux.—Plateaux are elevated tablelands possessing a more or less undulating surface. Genetically they may be arranged in three dominant groups—

1. Plateaux of arid erosion.
2. Basaltic plateaux.
3. Block-plateaux.

Plateaux of Arid Erosion.—An elevated region that has been subjected to subaerial erosion in an arid region in time becomes worn down to a plateau or peneplain. Typical plateaux of this kind occupy nearly the whole of the interior of the Australian continent. They appear almost level when viewed in distant perspective, but when travelled over are found to be diversified with rocky knobs, minor elevations, river gorges, and fault-escarpments.

Many of the prominent mountains, as seen from the coast, are only the scarps of the inland plateaux.

The plateaux which occupy the interior of South and Central Africa are high peneplains of arid erosion.

Basaltic Plateaux.—These have been formed by floods of basaltic lavas that have issued from volcanic vents of the fissure type. Notable examples are the Deccan Plateau, the North Atlantic Plateau, and the great plateaux of Idaho, Oregon, Washington, and California.

The Deccan basalts cover an area of about 200,000 square miles. Near Linga, in the Central Province, there are five flows, with an average thickness of 60 feet each.[1] They consist of basalts, vesicular and fine-grained at the top and bottom, but passing into comparatively coarse dolerites in the centre of the flows. They rest directly on Archæan granites and gneisses. The flows are separated from one another not only by vesicular surfaces, but usually by a small thickness of freshwater fossiliferous sediments, or of green earth, or of both together. The green earth has been formed by the alteration of the base of each flow. The flows were originally horizontal, but are now bent into a series of gentle anticlines and synclines whose axes are, curiously enough, parallel with the direction of the foliation of the Archæan gneisses.

The North Atlantic Plateau is believed to extend from North-West Britain through Iceland to Greenland on the one hand, and to the Faroes on the other. Only small remnants of this once great basaltic sheet now remain.

The lava-covered deserts of Western America cover an area as large as that of the Deccan plateau.

Block-Plateaux.—These are platforms arising from the uplift of crustal segments. They are bounded by powerful faults.

The beautiful table-topped block-mountains in Central Otago in New Zealand are remarkably fine examples of this type of plateau.

Valleys.

The term *valley* is applied to the longitudinal hollow or depression through which a stream or river flows. In arid and recently glaciated regions many valleys and gulches are not drained by a stream, and hence are called *dry-valleys* or *dry-gullies*.

The river-valley proper should be clearly distinguished from the channel in which the river pursues its downward course to the sea.

[1] L. L. Fermor and C. S. Fox, *Records of the Geo. Surv. of India*, vol. xlii., 1916; and R. D. Oldham, *Manual Geol. of India*, 1893, p. 275.

The valley proper may be bounded by low undulating downs, low foothills, high foothills, ridges, or mountain-chains.

The ridges bounding a valley are sharply defined; they are called the *valley-walls*.

Genesis of Valleys.—Practically most valleys are the work of subaerial erosion. Their initial direction or course may arise from different causes. Among the principal of these determining causes are—

(*a*) *A powerful fault* or dislocation that forms a depression or rift along its course.
(*b*) *A series of parallel faults* giving rise to longitudinal strips of sunken areas, forming what are called *rift-valleys* or *graben*. The stationary areas forming the valley-walls have already been described as *horsts* or *block-mountains*.
(*c*) *A shear-zone* along which the country-rock may be so shattered and broken as to be easily attacked by fluviatile or arid erosion.
(*d*) *Earthquake and volcanic rents.*—The great fissure-rent formed by the Tarawera eruption in 1886 has become the channel of a considerable stream, and is already assuming the dimensions of a well-defined immature valley. Earthquake rents that coincide with old fault-lines have in many regions become stream channels that will in time develop into valleys.
(*e*) *Zones of soft rock* bounded by hard rock, giving rise to what may be called differential erosion by pluvial, glacial, or arid agencies. While the direction of most trunk-valleys is probably determined by faulting or some other structural cause, it is certain that the direction and existence of most of the numerous lateral valleys is due to differential erosion. A soft series of strata may be repeatedly brought to the surface by acute folding or faulting, giving rise to the formation of a number of more or less parallel valleys bounded by steep escarpments.

Fault-scarps may become so frayed by erosion as to be no longer parallel to the original fault-line.
(*f*) *Simple synclinal folding* in recently disturbed areas. It is not often that the surface configuration coincides with the underground arrangement of the strata; except in immature valleys where the amount of erosion that has taken place since the folding of the strata is insignificant.

Soundings undertaken during recent years have brought out the striking fact that the submarine continuations of many rivers can be traced to the edge of the continental platform, where they descend through narrow gorges into the abyssal floor of the ocean. Notable examples of rivers whose courses can thus be traced are the Congo, Tagus, and Shannon. These submarine troughs would indicate a considerable subsidence of the eastern Atlantic borders, always provided they are true valleys of subærial erosion, and not the seaward continuation of rifts or *graben* resulting from faulting. The subsidence is perhaps only the effect of the rise of sea-level produced by the melting of the Pleistocene ice-sheets.

The deep gutter which passes through the Moray Firth probably marks the course of the glacial Spey when it ran northwards and joined the older and greater Rhine.

A deep groove surrounds the coast of Norway, and cuts off that region

from the shallow plateau of the North Sea. It is a geographical feature of great interest, but its meaning and origin are not yet well understood.

Probably all great valleys are connected with powerful crustal dislocations.

Rift-Valleys.—These frequently form physiographical features of vast importance. Perhaps the most remarkable is the great rift-valley of Syria and the Red Sea. This depression forms the valley of the Jordan and the basin of the Dead Sea, the surface of which lies 1300 feet below the level of the Mediterranean. From the Dead Sea it pursues a southerly course down the Gulf of Akaba, and, curving to the south-east, forms the trough of the Red Sea.

The Shire Valley and Lake Nyasa form the southern portion of one of the greatest rifts in the African Continent. This depression, with a break at the north end of Nyasa, runs northward for 400 miles through Lakes Rukwa and Tanganyika ; and with a few short breaks passes through Lakes Kivu, Albert Edward, and Albert, and thence on to the Nile.

In Central Asia the Tianshan Rift Valley lies 500 feet below sea-level, while the mountain chain Bogdo-ola, facing it to the north, reaches a height of 20,000 feet.

Fault-Valleys.—Most Alpine chains are intersected by deep transverse valleys that cut back to the main divide, and end in a pass, saddle, or *col.* Across the pass there is frequently another valley which intersects the range on the opposite side. In many cases it is possible to cross a high inaccessible chain by ascending one valley and descending the opposite one.

The two valleys which meet at the pass sometimes follow the course of a powerful fault or shear-zone running transversely across the main chain. Such valleys are dislocation rifts widened out by subsequent erosion, and hence are essentially different from the *graben* or strips of subsidence already described.

Cañons.—In the cañon region of Colorado the horizontal, Cretaceous and older strata form an ancient plateau which has become intersected by numerous deep gorges formed by fluviatile erosion (see Frontispiece). The cañons do not follow faults or lines of dislocation. In the beginning they were probably simple joint fissures that gradually became enlarged by river-erosion during the progress of the uplift.

The great depth, narrowness, steepness, and U-form of the cañons show that the excavation has been relatively rapid. Moreover, the cycle of erosion is still in the juvenile or torrential stage.

Form of Valleys.—The form of practically all valleys has been modified by pluvial or glacial erosion, or by the united activity of both, or by arid erosion. Subærial erosion will always be greatest where the rocks are softest, or where they are so broken as to offer the least resistance.

The form of the cross-section of a valley at any point will depend on the maturity of the valley, the resistance offered by the rocks, and the character of the eroding agency.

In a juvenile valley the cross-section will be V-shaped ; and in the uplands the river will occupy the whole width of the floor of the valley, in the torrential portion of its course running in a narrow gutter excavated in the solid rock, and in the middle portion wandering over a wide shingle-bed which may vary, according to local circumstances, from a few yards to many miles wide.

In a river-system which has reached maturity the valley is wide and the walls are not very clearly defined. In this portion of its course the river usually occupies a well-defined channel.

A typical river-system usually exhibits three phases or tracts of erosion,

namely: (*a*) a *torrent-tract*, where erosion is at a maximum and deposition at a minimum; (*b*) a *valley-tract*, where the gradients are flatter and erosion consequently slower—here also the valley-walls are flatter and deposition of detritus is taking place in favourable situations; (*c*) the *plain-tract*, where erosion has practically ceased and deposition is at a maximum.

Obviously the *plain-tract*, which has been subjected to erosion the longest, shows the flattest gradients and lowest relief. In the *torrent-tract*, which comprises the latest territory added to the river-system—the frontier, where the tributaries are continually extending their sphere of influence—the contours are steep and rugged.

As erosion proceeds, the plain-tract encroaches on the valley-tract, and the valley-tract on the torrent-tract, which in its turn is continually reaching out into new territory. It is in the plain-tract that a river-system first reaches its base-level of erosion.

Glaciated-Valleys.—Glaciated-valleys are usually distinguished by flat bottoms and smooth even walls. In relatively soft rock the projecting spurs or ridges are faceted so as to present tent-shaped ends; but where the rock is

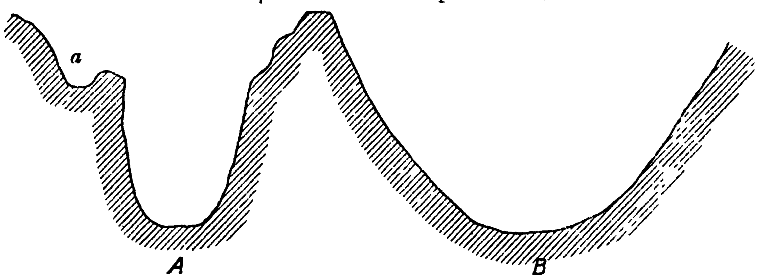


FIG. 225.—*A*, Cross-section in hard rock with corrie lake on high shoulder at *a*; *B*, Gentle slope in soft rock.

hard, the ice may ride over the spurs, the crests of which are truncated into flat platforms.

Ridges of hard rock running parallel with the axis of the valley are usually worn into rounded whale-backed ridges or *roches moutonnées*.

The form of the cross-section of a glaciated-valley depends mainly on the hardness of the country-rock. Where the rock is granite, gneiss, or hard crystalline schists, the form approaches the U-shape; but where the rocks are soft schists, shales, or Tertiary strata, the walls are worn into gentle catenary curves. These forms are shown in fig. 225.

Drowned-Valleys.—When subsidence takes place in a maritime region intersected by deep valleys, the sea advances and floods the valleys, which thereby become converted into *sounds*, *fiords*, and *sea-lochs*. These partially submerged or *drowned valleys*, as they are called, possess the same contour forms below sea-level as above.

The beautiful fiords of Norway, Alaska, and New Zealand, with their numerous ramifying arms and inlets, are typical examples of drowned-valleys that have been modified by glacial erosion.

The fiords of Norway and New Zealand, and the sea-lochs of West Scotland, are usually deeper inside than at their mouths. The cause of this deepening may arise in some cases from accumulations of glacial débris deposited at the sea-face of the tongues of ice that occupied the valleys at the close of the Pleistocene; in others from the presence of lake-basins or depressions in the floor of valleys before the subsidence took place.

Drowned-valleys in non-glaciated regions do not exhibit this inside deepening, which may be regarded as characteristic of true fiords.

Fiords, it should here be noted, are not a feature peculiar to the sea-coast. The *freshwater fiords* on the west coast of Lake Te Anau, New Zealand, are profoundly deep, narrow, glaciated valleys, that extend back to the heart of the Alpine chain, and in general outline and character are typical of the well-known *sea-fiords* on the opposite side of the chain.

Lakes.

A lake is a body of water entirely surrounded by land. The term is usually restricted to sheets of water sufficiently large to form physiographical features of some importance. The smaller bodies of water are called *tarns, meres, corrie lakes*, and *pools.*

Genetically considered, lakes and tarns may be classified in five main groups—

(1) Tectonic lakes, or lakes due to differential earth-movement.
(2) Glacial lakes.
(3) Barrier lakes.
(4) Crater lakes.
(5) Dissolution lakes.

Lakes due to Differential Earth-Movement.—This class comprises the largest and most important sheets of water, which, according to local conditions, may be salt, brackish, or fresh. As a rule they are situated in plains or plateaux.

The Caspian Sea and Sea of Aral, which occupy portions of the same crustal depression and were at one time united, are good examples of inland salt-water lakes that have been detached from the ocean by crustal movement. The faunal evidence seems to point to a former connection with the Arctic Ocean, and the physiographical evidence to a connection with the Black Sea depression. The mean water-level of the Caspian Sea is 84 feet below that of the Black Sea ; and of the Sea of Aral, 128 feet above that datum—differences of level which may be ascribed to crustal warping.

Estuaries and arms of the sea that have become detached by uplift or crustal tilting may increase in salinity in arid regions, or become fresher in regions where the inflow of fresh water exceeds the evaporation. Conversely, a fresh-water lake in a region of increasing aridity may become saline and in time present many of the features of a salt-water lake that has been cut off from the ocean.

The Dead Sea lying in the depression of the Syrian Rift-Valley is extremely saline, while the great lakes situated in depressions along the course of the East African Rift-Valley are fresh. The Great Salt Lake of Utah situated in the Great Basin is merely the shrunken remnant of a large inland lake that owed its origin tc crustal deformation.

The deepest known lake is Lake Baikal, in Siberia, which owes its existence to profound crustal puckering. Its surface lies about 1350 feet above the sea ; and as its greatest depth is 4500 feet, the deepest part of its bottom lies over 3000 feet below sea-level.

Glacial Lakes.—These are situated in recently glaciated regions, and, as a rule, occupy depressions in narrow Alpine valleys. Good examples are Lakes Como and Maggiore on the Italian side of the Alps, and Lake Wakatipu in New Zealand.

Glacial lakes frequently occupy rock-basins which may be many hundred

feet deep; but the depth of most lakes of this class is increased by barriers t the outlet composed of morainic and fluvio-glacial detritus.

The erosive effect of a glacier is proportional to the thickness of the ice. A stream of ice, like a river, tends to elongate and deepen the depressions in its bed. In this way certain parts of glacial valleys have become over-deepened, and now form lake-basins.

The erosive effect will be greatest in soft strata, or in zones of rock crushed and broken by faulting or shearing.

Many corrie lakes that occupy niche-like indentations on the brow of mountain slopes and on the flat shoulders of valley-walls, rest in rock-basins that were excavated by ice during the Glacial Period.

Barrier Lakes.—Some Alpine lakes have been formed by the blocking up of the valleys by glacial detritus; but most Alpine lakes, as mentioned above, are partly barrier and partly rock-cut.

The circular tarns or corrie lakes found in glacial cirques are frequently held up by accumulations of snow-piled rocky detritus, but many occupy true rock-basins.

Barrier lakes are sometimes formed in mountainous regions by extensive land-slips, avalanches, or ice-jams, but they do not form permanent geographical features.

Marginal Glacial Lakes.—When a continental ice-sheet advances across the divide separating one watershed from another, the drainage from the ice-front will flow down the invaded valleys without hindrance, and where the topographical features are favourable, wide valley-trains of fluvio-glacial drift may be formed. But when the ice retreats behind the dividing range, the drainage will be dammed between the high land and the ice-front, thereby forming a marginal lake which will increase in size and depth as the ice-recession progresses, till a natural outlet is formed. The site of such glacial lakes will be marked by high-level beaches and lacustrine deposits.

Many fine examples of Pleistocene glacial lakes existed in the Laurentian Lake Region of North America, along the ice-front of the Keewatin and Labradorian ice-sheets.

When the Mesabi and Giants ranges were completely covered with ice, and the ice-front lay to the south of these transverse barriers, the drainage passed down the Mississippi Valley; but when the ice-sheet retreated into the Lake Superior basin, on the north side of the dividing ranges, the drainage was held up between the high land on the south and the retreating ice, thereby forming great marginal lakes, the largest and most notable of which has been called Glacial Lake Agassiz, so named after the distinguished Swiss naturalist Agassiz, who was the first to recognise the evidences of a Pleistocene extension of the Arctic ice-sheet in northern continental Europe and Scotland. As the ice-sheet receded Lake Agassiz grew in size, till the whole lacustrine area, as estimated by Warren Upham,[1] exceeded 110,000 square miles, or more than the united area of all the present Laurentian lakes.

The three detrital terraces or benches, forming what are known as the *Parallel Roads* of Glen Roy in the Highlands of Scotland, are believed by some writers to be the beaches of a lake formed by a barrier of glacier-ice.

Rivers are sometimes blocked at their mouths by ridges of wind-blown sands, whereby large shallow lagoons or basins are formed near the sea. In some maritime regions the mouths of the rivers are blocked by wide stretches of shingle cast up by powerful tides. Many capacious lake-like harbours of great value have been formed in this way on exposed storm-beaten coasts.

[1] *The Glacial Lake Agassiz*, Monograph xxv., U.S. Geol. Survey, 1894, p. 214.

Crater Lakes.—These occupy the craters of extinct or dormant volcanoes. Good examples of these may be seen in the Eifel, Auvergne, Central Italy, and North New Zealand.

The depressions formed by explosive volcanic outbursts frequently form lakes of considerable extent. Lake Rotomahana in New Zealand occupies a portion of the great fissure-rent formed by the Tarawera eruption in 1886. In the same region many large lakes, notably Lakes Taupo and Rotorua, have been formed by local subsidence in the neighbourhood of old centres of eruption situated on the Central Volcanic Plateau.

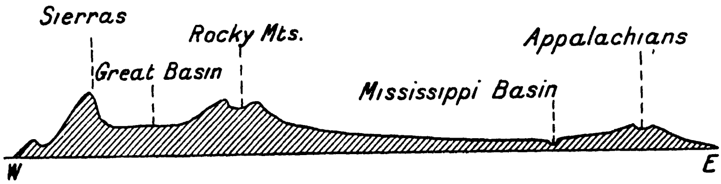


FIG. 226.—Showing profile of North America.

The lavas and ejectamenta of volcanic eruptions have in some cases formed barriers across valleys whereby the natural drainage has been impounded, thereby forming lakes. The Yellowstone Lake is confined by a barrier of lava, and also the Lac d'Aydat of Auvergne.

Dissolution Lakes.—These are formed in limestone regions, and arise from the dissolution of the limestone by the carbonic acid contained in the ground water. It is probable that most of the lakes in the limestone districts of Ireland belong to this class.

FIG. 227.—Showing profile of South America.

Continental Forms.

When we take a broad survey of the great continents, we are impressed with certain outstanding physiographical features that seem to suggest a relationship between the continents and the bordering oceans. This relationship has been expressed by Dana in two postulates as follows :—

(1) The continents have in general elevated mountain borders and a low or basin-like interior.

(2) Th highest border faces the larger ocean.

America.—In North America (fig. 226) we have the Rocky Mountains on the Pacific side (the side of the greater ocean), and the Appalachians on the Atlantic side. Between these chains lies the great interior plain.

In South America (fig. 227) the great Andes Chain faces the Pacific (the larger ocean), and a low coastal range faces the Atlantic.

The Bolivian plateau lies between the Western Cordillera (*a*) and the Eastern or Bolivian Cordillera (*b*); while on the east coast we have the low ranges of Venezuela and Guiana.

Europe.—This continent does not present the well-defined coastal arrange-

ment of the mountain-chains of North America. Moreover, the great chains, as in Asia, follow a general east and west course.

On the south side of Europe we have the Pyrenees, Alps, Carpathians, and Caucasus; and on the north the mountains of Scandinavia. Between these lie the Baltic depression, the vast plains of North Germany, and Baltic provinces of Russia, altogether occupying three-fifths of the area of all Europe.

Asia (fig. 228).—Facing the open Indian Ocean stands the Himalayas; and in Central Asia the Altai Mountains face the great steppes and tundras of Northern Siberia, which extend northwards to the Arctic Ocean. Between these chains lie the plains of Mongolia and the Desert of Gobi.

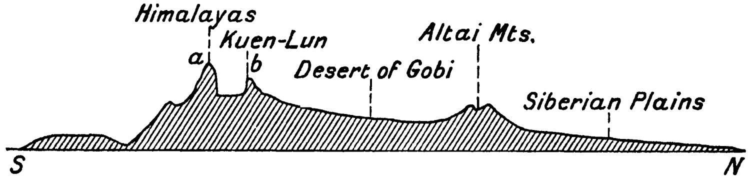


FIG. 228.—Showing profile of Asia.

Africa.—This continent is dominated by plateau forms, long continued denudation having truncated or altogether effaced the mountain-chains.

A high rim of land faces the Indian Ocean, and as a result the drainage of the interior is westward and northward, the Zambesi being the only river to break through to the Indian Ocean.

Australia.—The plateau form of Australia is even more conspicuous than that of Africa. A rim of mountains—the Australian Alps—borders the eastern side of the continent, as shown in fig. 229, and on the west lies the Great Western Plateau.

Continental Islands.—These are portions of land separated from the main-

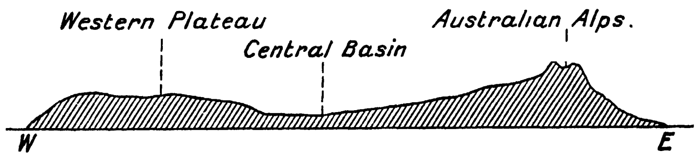


FIG. 229.—Showing profile of Australia.

land either by subsidence or marine erosion, or by the united action of both. Their geological structure is similar to that of the mainland, and hence, though separated by a stretch of water, they belong to the same geological province. Great Britain, Vancouver Island, Tasmania, and Madagascar are good examples of Continental Islands. Most of the great continents are festooned with islands of this type. Some islands of the continental type, like New Caledonia and New Zealand, are far from the mainland, this arising from the subsidence of wide crustal blocks.

Oceanic Islands.—These are, as a rule, far from a continental area; and perhaps most of them are of volcanic origin, though many have been built up by calcareous organisms in the form of coral reefs. As a result of their isolation and restricted environment, the endemic fauna and flora of oceanic islands usually include many peculiar forms, while the land mammals of continental regions are sparingly represented.

Origin of Mountain-Building Movements.

Of all the problems that have to be unravelled by the geologist none is more difficult or complex than that which concerns itself with the causes that have given rise to mountain-building folds. As we have already mentioned, these were formerly believed to have arisen from the simple contraction of the crust consequent on cooling. The nucleus decreasing in volume was supposed to shrink away from the outer crust which, being unsupported, possessed a tendency to pucker and adjust itself to the smaller nuclear dimensions.

Dana, like Elie de Beaumont, considered that slow cooling and contraction of the Earth's nucleus was the fundamental cause of crustal deformation; but he assumed that the limits of mountain-chains were determined by certain pre-existing lines of minimum resistance associated with irregularities in thickness and temperature in the Earth's crust. He argued that, as the primitive Earth cooled, the first crust-blocks that consolidated formed continents, and the pressure caused by shrinkage was most intense at the continental margins, where in consequence the greatest mountain-systems developed.

And, as a rule, the height of the mountain range corresponded to a depression in the neighbouring portion of the ocean-floor. He also assumed that the centripetal movement of the crust, as it endeavoured to shrink along with the nucleus, was changed into tangential stress, comparable with the stresses set up in a falling arch.

In Dana's opinion the horizontal pressure components originated in this way, and folded the crust into arched ridges and trough-like hollows. The latter he called **geo-synclinals,** and the former **ge-anticlinals**. He postulated that the mountain systems, composed of several chains, always arise within geo-synclinals where vast accumulations of sediments take place, sinking and deposition going on concurrently, so that the depth of water remains constant.

Reade's Cubical Expansion Theory.—Like Dana, Mellard Reade assumes that mountain-building takes place only in regions of great sedimentation. He postulates that there is an increase of temperature in these parts proportional to the thickness; and whereas Dana and Lyell believed that the force of expansion arising from the increase of temperature acts only vertically upward, Reade shows that this force must tend to expand rocks cubically, *i.e.* is downward, upward, and laterally. The tendency to expand laterally is opposed by the less heated rocks in adjacent areas, and compression of the expanding rocks causes them to fold and buckle.

The rocky floor on which the sediments rest rises in temperature, and hence the ancient strata composing the floor expand, under the influence of the heat; and are compressed and folded, and in their semi-plastic state are pressed along the lines of least resistance in the mountain system situated in the anticlinal axes of the folds and arches. In this way we get the gneisses and other highly altered rocks in the core of the high mountain-chains.[1]

Professor Joly [2] believes that radio-activity may be important in mountain-building as a supplementary factor in accordance with Reade's theory. He contends that a temperature that will soften an average igneous rock will not soften a sedimentary rock for the reason that the effect of solvent denudation has been to remove the easily fusible alkaline silicates. This deficiency of heat, he thinks, is compensated by the heat emanating from the radium content of the sediments. He estimates that in a succession of beds, 40,000 feet in thickness, there will be an elevation of about 111° C. above that which

[1] T. Mellard Reade, *The Origin of Mountain Ranges*, London, 1886, pp. 326–330.

[2] *Radio-activity and Geology*, 1909, p. 103.

similar materials under the same conditions, but without radio-active ingredients, would experience.

Professor J. W. Gregory[1] calls in question the value of some of Joly's data. He contends that no theory of mountain formation is complete unless it explains the distribution of mountain-chains, and the only theory that attempts such an explanation is that which represents the Earth's crust as distributed by two series of movements. There is a slow heaving, which gently uplifts and lowers wide areas, and there is the violent compression of long, narrow bands, which are crumpled, faulted, and smashed; and these bands are upraised into mountain folds.

The theory of geo-synclinal sedimentation was opposed by James Geikie, who believed that folded mountains owe their origin to the sinking of crustal segments upon the cooling and contracting nucleus.

The theory that most nearly satisfies the facts is a combination of the hypothesis of geo-synclinal sedimentation and the cubical expansion of the rocks under the influence of heat. The relatively narrow bands that become folded into mountain-chains may arise from the existence of pre-existing blocks of rigid rock against which the travelling movement has crumpled and crushed the younger strata.

Arcuate Mountain-Chains.—As early as 1881, Prof. J. Muschketoff, in a description of the morphology of the mountains of Turkestan, recognised the arc-like form of the Thian-shan chains which, he says, present their convex side towards the ocean. Following up this line of investigation, Prof. Suess (1904), in a discussion on the form and origin of the great mountain systems of Eurasia, recognises five great arcs that turn towards the south and align themselves one after the other across the continent. These he calls the Malay arc, the arc of the Himalaya, the shattered outer arc of the Hindu Kush, the Iranian and the Dinaro-Tauric arc. To these he added the great arc surrounding the western Mediterranean.

These arcs separate the table-land of North Africa and Arabia, and that of the Indian peninsula, from the folded regions in the north; and they have a definite relationship to the geological structure of the regions in which they occur.

In Asia nearly all the chains take the forms of arcs having their convex faces turned toward the ocean areas. This feature is also exhibited in the island-festoons that fringe the eastern border of the continent; and these continental islands also present their convex faces to the ocean. The Balkan Mountains, Carpathians, and Alps have the form of great curves.

The arcuate form of these great mountain-chains has arisen from the existence of masses of rigid rock masses or shields, that offered such effective resistance that the travelling crustal wave was compelled to make a sweeping curve around them. All writers are not agreed as to the dynamics of this curved mountain structure, but whether we assume the earth-movement to have travelled from a centre outward, or from an outer region inwards, the significant fact remains that the development of the chains and their arc-like form have been mainly determined by the antecedent geological structure of the region where the mountain-chain originated.[2]

[1] *Geology of To-day*, 1915, pp. 148–149.

[2] E. Suess, *The Face of the Earth*, vol. i., chap. viii., pp. 463–507; and W. H. Hobbs, "Mechanics of Formation of Arcuate Mountains," *Jour. of Geology*, vol. xxii., 1914, parts i., ii., iii., p. 71.

PART III.

CHAPTER XXXVI.

ECONOMIC GEOLOGY.

ECONOMIC or Mining Geology is mainly concerned with the occurrence and genesis of ores and mineral deposits; with coal and mineral oil; building-stones and roofing-slates; flagstones and road-metal; limestones and cements; grindstones and whetstones; ornamental stones and marbles; clays for brick-making and pottery; sand for glass-making; soils; and with the supply of underground water for domestic, manufacturing, agricultural, and medicinal purposes.

Ores and Mineral Deposits.

Mineral deposits mostly occur as *veins* or *lodes* traversing rock-masses, or as *sheets*, *layers*, or *beds* interbedded with and forming part of rock-formations.

In regions which have suffered considerable denudation, the valuable contents of veins and mineral deposits may be concentrated in the sands, gravels, or other detritus laid down along the course of the streams and rivers, or on sea-beaches. Such deposits are called *alluvial* or *detrital*, and are obviously of secondary origin.

Definitions.—A *vein* or *lode* may be defined as a more or less continuous sheet-like body of ore enclosed within rocky walls. It may be horizontal or vertical, or inclined at any angle.

The term *vein* is frequently restricted to designate the simple sheets of relatively small dimensions possessing well-defined walls; while the term *lode* is more often applied to the larger ore-bodies, or to zones or bands of mineralised rock that contain strings, bunches, or ramifying veins or veinlets of valuable ore.

An *ore* may be defined as any rock or mineral from which one or more metals or minerals may be profitably extracted. It therefore excludes such substances as slate, chalk, clay, and building-stones, but may include sulphur or borax.

A *lens* or *lenticle* of ore is one shaped like a biconvex or plano-convex lens. Such deposits taper out to small dimensions in all directions, or *peter* out altogether.

Mineral Deposits Morphologically Considered.

Classification.—Mineral deposits are found in many different forms and under many varying conditions. Moreover, they present a great diversity of origin. Hence they may be considered *morphologically*—that is, according to their outward form, or *genetically*, according to their origin. Of these,

outward form and mode of occurrence offer the most convenient starting-place for the elementary investigation.

The *morphological* classification, based on outward form and mode of occurrence, but entirely independent of age or mineral character, is as follows :—

Class I.—Superficial mineral deposits.
Class II.—Stratified mineral deposits.
Class III.—Unstratified mineral deposits.

For convenience of study and description these classes are subdivided into groups or sub-classes—

I.—Superficial Deposits.

(*a*) *Detrital*—Forming or occurring in alluvial drifts.
(*b*) *Massive*—Forming superficial layers and sheets.

II.—Stratified Deposits.

(*a*) *Constituting beds*—Forming members of a stratified formation.
(*b*) *Disseminated through a bed.*

III.—Unstratified Deposits.

(*a*) *Deposits of volcanic origin.*
(*b*) *Stockwork deposits.*
(*c*) *Contact and replacement deposits.*
(*d*) *Fahlbands.*
(*e*) *Impregnations.*
(*f*) *Segregated veins.*
(*g*) *Gash-veins.*
(*h*) *True-veins.*

Class I.

Superficial Deposits.

(*a*) **Detrital.**—Alluvial or *placer* deposits, as they are usually called, embrace detrital deposits of all kinds, whether beach sands, river gravels, lacustrine gravels, or glacial drifts, containing particles of gold, platinum, tin-ore, iron ores, emeralds, rubies, diamonds, or other precious stones.

The alluvial deposits may be of recent date or of great antiquity. They may exist as sands and gravels in the bed or bank of a stream ; or form terraces ranging in age from the Pleistocene to almost recent times ; or occur as so-called *deep-leads* which are merely river-drifts of Pliocene and later date covered over and protected by sheets of basaltic lava ; or occur as consolidated gravels or conglomerates interbedded with rocks ranging in age from the Silurian to the late Cainozoic.

The most widely distributed and valuable of alluvial deposits are those of gold. The alluvial gold originated from the weathering and denudation of country containing gold-bearing veins during countless centuries, followed by the concentration of the liberated particles and nuggets of gold in the gravelly bed of the streams and rivers by a process of natural sluicing.

The gold, owing to its great specific gravity, gravitates toward the bottom

of the drifts and usually lodges on or near the bed-rock (fig. 230). The crevices in the bed-rock, which is frequently slate, sandstone, or mica-schist, offer a convenient and safe lodgment for the travelling particles of gold.

The portion of the gravel drift which contains the gold is called the *pay-wash*.

The pay-wash usually lies on the bed-rock, or *true-bottom* or *reef-bottom* as it is called, but in thick accumulations of river-drift, two, three, or more

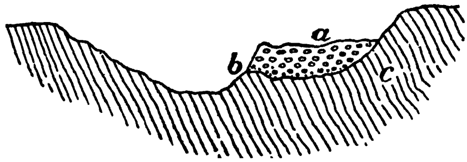


Fig. 230.—Section of gold-bearing river-terrace.
(*a*) Terrace gravels. (*b*) Pay-wash. (*c*) Slate bed-rock.

layers of pay-wash may exist, each resting on a bed of clay or distinctive bed of gravel, which is called a *false-bottom*.

The most valuable gold-bearing drifts occur in California, the State of Victoria in Australia, and New Zealand.

Deep-leads of great value occur in California, and at Ballarat in Victoria (fig. 231), underlying thick sheets of basaltic lava of late Tertiary date.

Tin-bearing gravels of great extent and value occur in Malaysia, which produces the bulk of the world's annual supply of tin-ore.

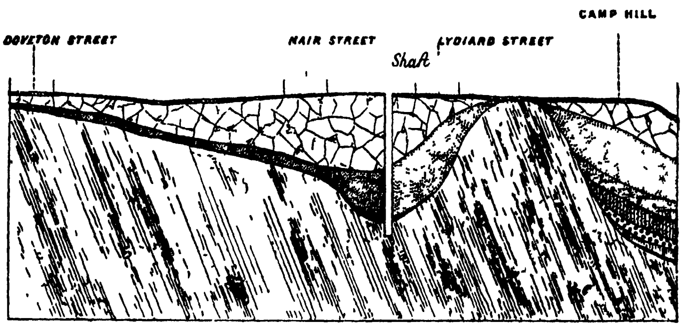


Fig. 231.—Showing deep-lead underlying sheet of basalt, Ballarat Goldfield, Victoria.

The platinum-bearing gravels on the eastern slopes of the Ural Mountains produce 90 per cent. of the platinum of commerce.

Diamond-bearing gravels occur on the banks and bed of the Vaal River in South Africa, and ruby placers have been worked for centuries in Burma, and for many years in Brazil.

(*b*) **Massive.**—Deposits of this kind occur in superficial sheets, layers, or masses frequently covered with soil, clay, or other recent accumulations. They include deposits of bog iron-ore, laterite, rock-salt, sulphur, and rock-phosphate.

Bog Iron-Ore is an impure hydrated peroxide of iron which frequently forms on the bottom of swamps and shallow lagoons.

Laterite is mainly composed of alumina and iron oxide, with sometimes manganese and titanium. When the surface of a flow of basaltic or other

basic lava is exposed to the weathering action of the atmosphere in a warm moist climate, the carbonic acid in the air, in conjunction with water, attacks the felspars and removes the silica, lime, magnesium, potash, and soda in solution. The alumina and iron are left behind as a reddish-brown or brick-red sheet of earthy ironstone.

The brick-red layers of lateritic clay frequently seen in ancient volcanic regions intercalated among lava-flows and beds of ash are surfaces of lavas that have become weathered and decomposed during periods of cessation from volcanic activity.

Superficial layers of rock-salt occur in the dried-up swamps and lagoons in the arid regions of Asia, North America, and Australia. Deposits of sulphur occur in volcanic regions, and rock-phosphates are often found on the chemically eroded surfaces of limestones, where they have accumulated by a process of secondary concentration.

Class II.

Stratified Deposits.

(*a*) **Constituting Beds of Strata.**—The useful minerals which occur in beds or as members of a stratified formation are coal, oil-shale, iron-ore, and rock-salt.

Coal is a combustible mineral substance resulting from the alteration of organic and preponderatingly vegetable matter. It occurs in beds or *seams* which vary from a mere streak to 300 feet thick. These thicknesses are attained by brown coals.

The numerous varieties of coal which occur are—

1. Peat.
2. Lignite.
3. Brown coal.
4. Cannel coal.
5. Bituminous or coking coal.
6. Semi-anthracite.
7. Anthracite.

The principal coal-bearing formations are the Carboniferous in Britain, Belgium, and North America; Permo-Carboniferous in New South Wales and India; and Eocene and Miocene in New Zealand.

Some brown coals are Upper Cretaceous, as in New Zealand, but in most countries they are Lower and Middle Cainozoic, as in Texas, South Hungary, North Germany, and New Zealand.

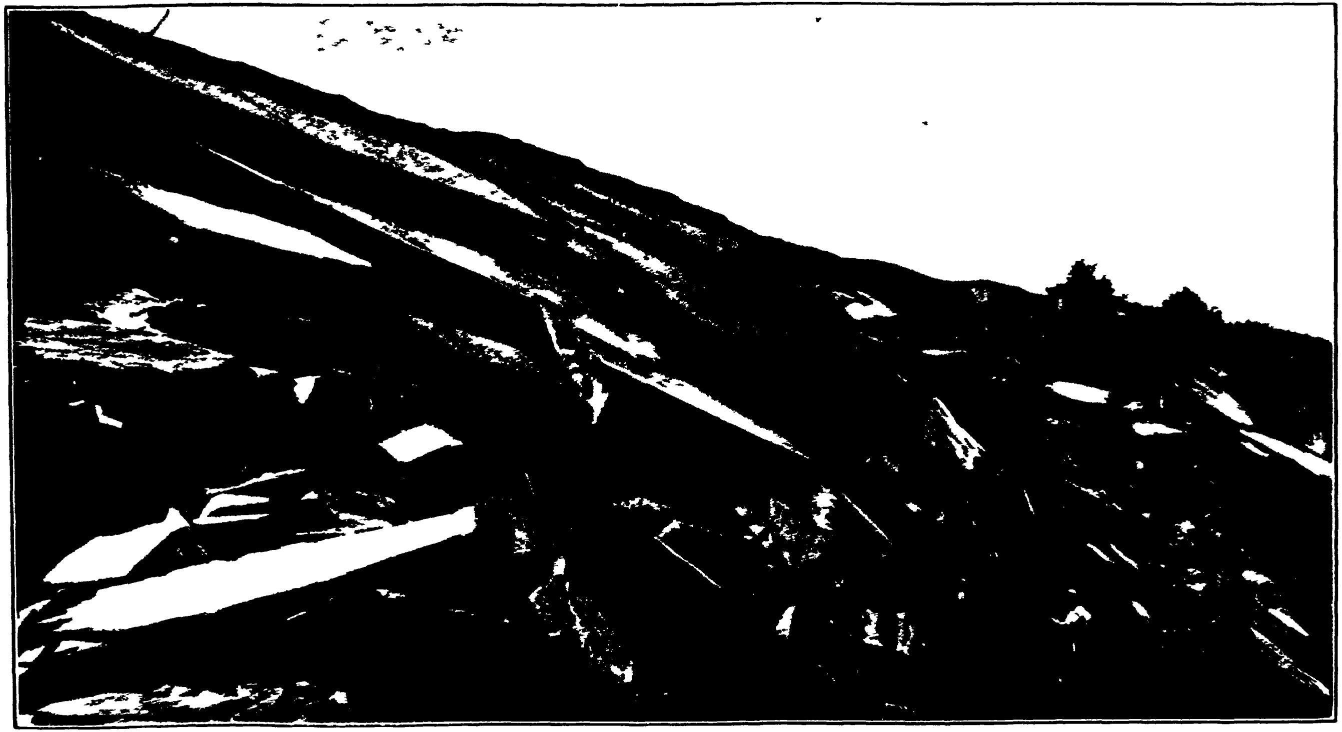
Lignites are mostly of Pliocene and Pleistocene age.

Coal-seams may be horizontal, or inclined, folded, bent, or over-turned (fig. 232), according to the amount of disturbance suffered by the strata in which they are enclosed.

Oil-Shales occur in Carboniferous rocks in the Lothians of Scotland, Permo-Carboniferous of New South Wales, and Lower Cainozoic of New Zealand. Oil is obtained from them by distillation.

Natural Mineral Oil is obtained by boring in California, Texas, Ohio, Pennsylvania, Baku, Burma, Borneo, and other regions. Its origin is supposed by some writers to be igneous or inorganic, but the bulk of the evidence seems to favour the view that it is organic, resulting from the destructive distillation of animal and vegetable organisms buried in marine and lacustrine sediments.

The oil is expelled as gases from the muds, shales, and calcareous deposits



CAMBRIAN GREEN SLATE QUARRY MIDDLE GRANVILLE, NEW YORK (After Dale, U S Geol Survey)

in which the organisms were buried, and is condensed into heavy oil in the overlying porous sandstones or strata, where it accumulates under great pressure.

When the impervious strata overlying the porous sandstones are penetrated by bore-holes, the oil and gases rise to the surface.

Beds of iron-ore occur in geological formations of different age. They form members of stratified series, and are often oolitic. Among others there are such bedded iron-ores in the Ordovician of North-Eastern France, and in the Jurassic of Lorraine. The chief minerals of these iron-ores are spathic iron and limonite.

Beds of *rock-salt* occur in many geological formations. Those of the Salt Range in the Punjab are Tertiary, although lying below Cambrian in consequence of overthrust; those of Cheshire, Triassic; while the famous salt-deposits of Wieliczka in Polish Austria are Miocene.

Other Bedded Deposits.—Among other bedded deposits of great value to man are Building-stones, Roofing-slates, Limestones, Flag-stones, and Road-metals, Clays, and Ornamental stones.

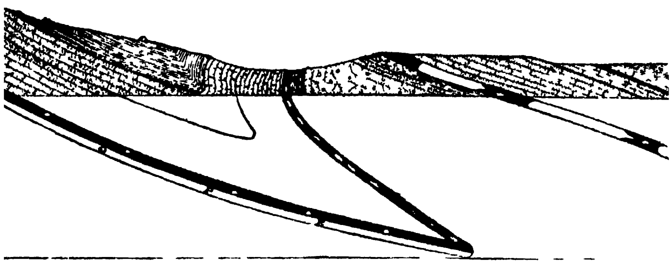


FIG. 232.—Section across Shenandoah Basin, Pennsylvania anthracite region, showing an overturned seam of coal.

The most valuable *Building-stones* are granite, sandstones, and limestones. Granite is hard, durable, and takes a fine polish. The siliceous sandstones are also hard and durable, while the softer calcareous sandstones or *freestones* are free-cutting, and hence of special value for the construction of front-walls and ornamental parts of buildings. The oolitic limestones of England and Continental Europe, and the magnesian limestones common in many parts of the globe, are valuable for all kinds of buildings

The best *Roofing-slates* are obtained from fine, even-grained, muddy sediments in which slaty-cleavage has been well developed. They are found in all the older Palæozoic formations in many parts of the globe. The Welsh roofing-slates are the best in Britain, and are seldom equalled in other regions.

Limestones containing 80 per cent. or more of carbonate of lime are valuable for burning into lime for agricultural purposes, and for the making of cement and mortar. Such limestones are found in almost all the rock-formations from the Cambrian to the late Cainozoic. In Britain the Wenlock or Dudley Limestone, the Carboniferous and Oolitic Limestones, and the Chalk are specially valuable. The impure, earthy limestones of the Jurassic and Cretaceous, so abundant in England, France, United States, and New Zealand, when calcined and pulverised, form natural *hydraulic cements* of great value. Portland cement is extensively manufactured from lime mixed with a suitable quantity of sea-mud or marl.

Common *Clays* are everywhere used for brick- and tile-making. The

clays of the Coal-Measures, from which the lime, soda, and potash have been exhausted by the growth of the coal-vegetation, are *refractory* or difficult to fuse, and hence valuable for the making of *fire-bricks* for the lining of furnaces, etc.

Pottery clays for the manufacture of china and porcelain ware are derived from the disintegration of granitic rocks. Cornwall and Devon have long been noted for their production of *Kaolin*.

Road-Metal is selected from the hardest and toughest rocks available, and those not subject to rapid disintegration. The best rocks for road-metal are granites, greywackes, siliceous sandstones, and quartzites. These are superior to such igneous rocks as dolerite, andesite, phonolite, and diorite, which are hard and tough, but disintegrate rapidly into mud under the influence of the organic acids liberated from road-refuse.

Flagstones are usually sandstones, schists, or limestones that can be readily split into thick flags. The famous calcareous flagstones of Caithness, of Old Red Sandstone age, are exported to all parts of the globe. Flagstones of slate, limestone, gneiss, and quartz-schist are extensively used, but natural stones are being largely replaced by artificial slabs of concrete and other stony mixtures.

Ornamental Stones are usually hewn from granites, gabbros, marbles, and serpentine. The grey granite of Cornwall, the grey and pink granites of Aberdeenshire, the Carboniferous and Devonian Limestones of Europe and America are much used as ornamental stones. The statuary marbles of Carrara, in the Trias of the Apennines, have long been celebrated for their pure colour and even texture.

Glass-making Sands are plentiful in the older Cainozoic formations of the United States, England, Brazil, and New Zealand at the base of the brown Coal-Measures.

Grindstones and *Millstones* are fashioned from gritstones and siliceous sandstones like the Millstone Grits of England.

Whetstones are often made from fine-grained lavas and siliceous slates or hornstones.

(*b*) **Disseminated through a Bed.**—Certain beds or strata of sedimentary formations are sometimes impregnated with valuable ores or minerals, the origin of which is uncertain. The metals were either introduced contemporaneously with the deposition of the sediments in which they occur, or after the consolidation of the sediments.

Among the most notable examples of this class of deposit are the famous gold-bearing *banket-reefs* of the Rand, in the Transvaal, which are merely beds of quartzose conglomerate impregnated with gold and pyrites; the celebrated copper-bearing shales of Mansfeld, in Prussian Saxony, which have been worked for eight hundred years; the rich copper-bearing conglomerates of Lake Superior; the Silver Sandstones of Utah; and the Lead Sandstones of Commern, in Rhenish Prussia.

Class III.

Unstratified Deposits.

(*a*) **Deposits of Volcanic Origin.**—These include deposits of sulphur and borax, which accumulate in and around fumaroles in the form of sublimates. The fumarolic sulphur of Vesuvius, Etna, and volcanic regions of Japan and New Zealand is of great economic value. The steam fumaroles of Pisa, in Italy, yield a large annual output of boric acid.

(*b*) **Stockwork Deposit.**—A Stockwork is a rock-mass traversed by numerous

small veins that mutually intersect one another (fig. 233), but are too small to be worked separately. The valuable ore may be tin, gold, or any metal of economic importance. With such deposits it is necessary to quarry the whole

FIG. 233.—Showing stockwork of magnesite veins, *U.S. Geol. Survey.*

of the rock-mass in order to extract the valuable mineral, hence the name *Stockwork*, which refers to the quarry-system of mining.

The celebrated gold-bearing ore-bodies at the Treadwell Mines in Alaska are good examples of this class of deposit.

(*c*) **Contact and Replacement Deposits.**—A Contact Deposit is one that

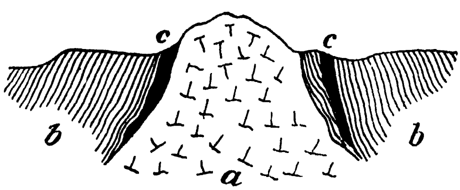


FIG. 234.—Showing section of contact deposits.
(*a*) Granite. (*b*) Slate. (*c*) Contact deposit.

occurs at or near the contact of a sedimentary rock and an intrusive mass or dyke (fig. 234).

Valuable deposits of iron-ores, and of copper, lead, and zinc sulphates are frequently found in the vicinity of intrusive dykes.

The famous copper-bearing pyritic ore-bodies at Rio Tinto, in Spain, are typical Contact Deposits.

(*d*) **Fahlbands.**—These are bands or zones of crystalline metamorphic rocks so highly impregnated with ore as to be of commercial value (fig. 235). The silver-bearing Fahlbands (grey beds) of Norway are among the best known examples. They follow the strike and dip of the strata by which they

are bounded. The thickness may vary from a few inches to hundreds of feet.

Fahlbands are related to bed-impregnation, and probably owe their origin to aqueous and gaseous emanations expelled from a cooling intrusive magma.

(*e*) **Impregnations.**—It has sometimes happened that when a rock has been fissured, a portion of the rock on one or both walls has become impregnated with some metallic substance, disseminated as grains, bunches, or nests through out the mass in the vicinity of the fissure (fig. 236).

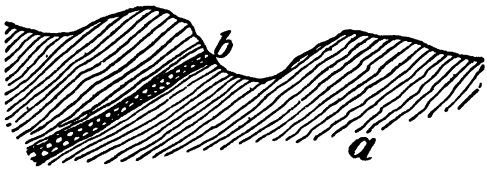


FIG. 235.—Showing fahlband at Dusky Sound, New Zealand.
(*a*) Mica-schist. (*b*) Fahlband of pyrrhotite, etc.

Such an occurrence is called an *Impregnation*, implying that the mineral has been introduced as a secondary product by mineralised waters, superheated steam, or gases.

The term "impregnation" refers to the genesis rather than the form of the ore-body. Genetically the majority of Stockworks, Contact Deposits, and Fahlbands may be regarded as impregnations, as well as such bedded deposits as the so-called Banket-reefs of the Rand, the copper-deposits of Mansfeld, the Silver Sandstones of Utah, etc.

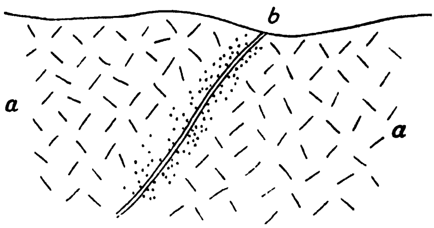


FIG. 236.—Tin-impregnation.
(*a*) Granite. (*b*) Tin-ore.

Granite and other acid igneous rocks are sometimes impregnated with tin-ore, and such tin-impregnations may be regarded as typical of this class of deposits. Among the most famous is the Mount Bischoff tin-deposit in Tasmania.

(*f*) **Segregated Veins.**—These are only found in sedimentary rocks which have been sharply folded, whereby fissures or cavities have been formed in the bent portions more or less parallel with the bedding planes. That is, Segregated Veins mostly occur along the crest of anticlinal axes, and sometimes along the axes of synclines.

The best example of Segregated Veins are *Saddle-Reefs*, which are typically developed at Bendigo, in the State of Victoria. These gold-bearing ore-bodies consist of arch-like masses of quartz that conform to the bedding planes and taper out going downward.

In what are called *Inverted Saddle-Reefs* the ore-bodies occur in the troughs

of the folds. Good examples of Inverted Saddle-Reefs are found at Mount Boppy, in New South Wales.

(*g*) **Gash-Veins.**—These are metalliferous deposits occupying lenticular or lens-shaped cavities or gashes in limestones. They usually occur at the intersection of cross-joints where cavities have been formed by the action of water, and simultaneously or subsequently filled with metallic ores. The ores that usually occur in this form are those of lead and zinc (fig. 239).

(*h*) **True Veins.**—These are the best defined and most persistent of all veins. They pass through all kinds of rock and pursue their course independently of the bedding planes or stratification. In some parts they may chance to coincide with the strike and dip of the enclosing rock-formation, and in such places they are difficult to distinguish from Segregated Veins.

All veins that crop out at the surface have been more or less truncated by denudation.

The mineral contents of True Veins were in most cases deposited by ascending aqueous solutions that were probably genetically connected with some deep-seated igneous intrusion.

The different minerals composing the vein-filling are frequently arranged in layers parallel with the walls. When the layers are made up of crystalline aggregates, the crystals are often arranged with the longer axis at right angles to the plane of the walls, thereby presenting the appearance called *comb-structure* (fig. 241).

The tin-lodes of Cornwall are typical examples of True Veins.

Filling of Cavities and Veins.—The vein-filling or *gangue* of lodes, in which the valuable metal or ore is embedded, is in most cases quartz, which may be crystallised or chalcedonic. Ores of lead and zinc are, however, usually enclosed in a gangue of fluor-spar or calcite.

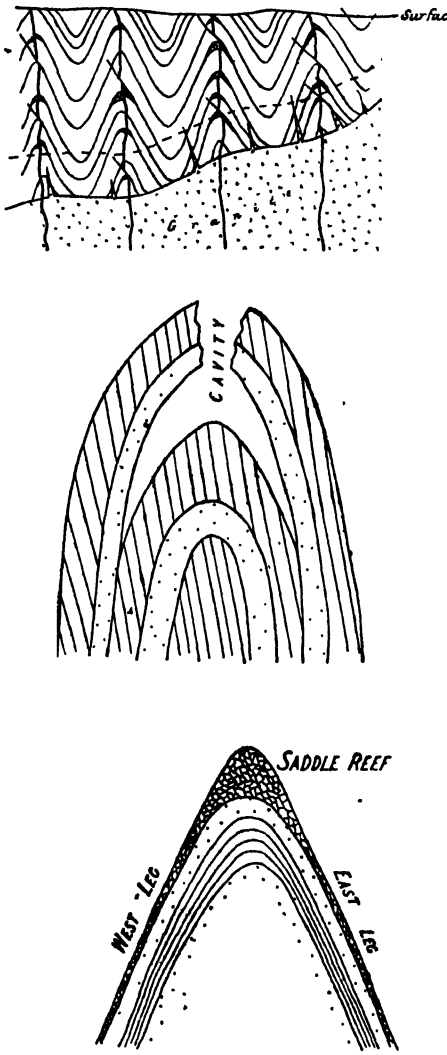


FIG. 237.—Sections showing formation of saddle-reefs. (After E. J. Dunn.)

Origin of Vein-Cavities.—The solutions that deposited the vein-matter and its valuable contents either found the cavities and fissures awaiting them, or they formed their own channels by a process of slow progressive

dissolution and replacement of the wall-rock along pre-existing cracks or fractures.

The pre-existing cavities and fractures were mechanically formed in sedimentary rocks by folding, or by igneous intrusions; and in eruptive rocks by contraction arising from cooling.

Where the fracturing of the rock has been produced by igneous intrusions,

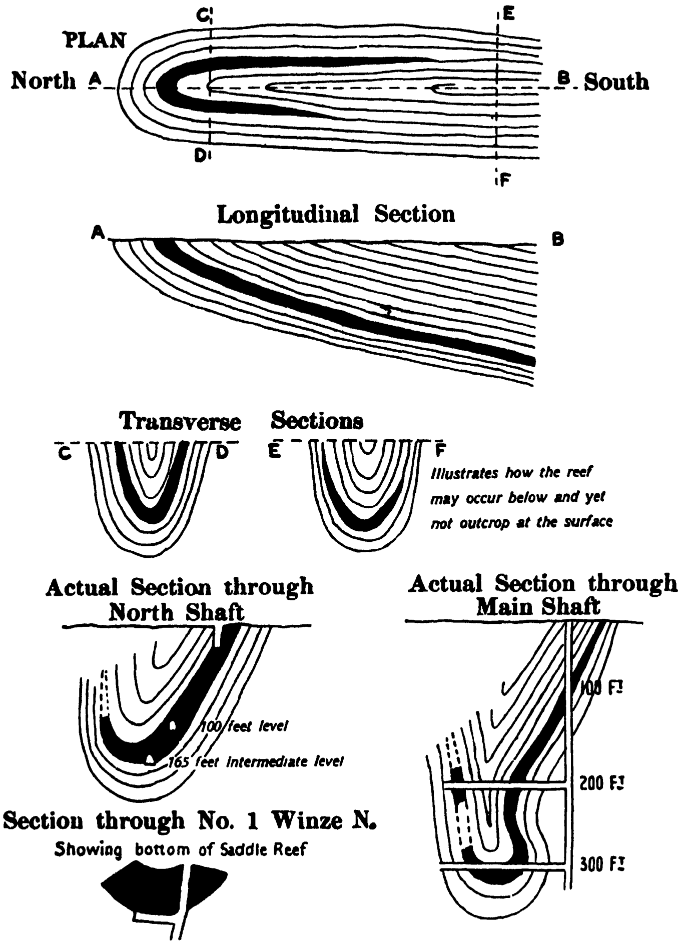


FIG. 238.—Sections showing structure of inverted saddle-reefs. (After Jaquet.)

these frequently provide the mineralised vapours and solutions that corrode the shattered rock and fill the fissures with mineral matter.

Ore-bodies are often formed along joint- and fault-planes, and at the intersections of joints, simple fractures, and faults (fig. 242).

Some rock-fissures are known to be of great antiquity from the presence of fossils in the material filling them. Dyke-like masses of sandstone containing Cambrian brachiopods occur in granite in the Åland Islands at the entrance of the Gulf of Finland; and narrow veins of fossiliferous sandstone are seen in

the sea-cliffs at Oamaru, New Zealand, traversing a sheet of basalt intercalated with Lower Miocene strata.

Depth of Lodes.—Where the lodes occupying fissures confined to a particular rock, or rock-formation, like the propylite-veins of Cripple Creek and Hauraki, or the gash-veins so frequently found in limestone, the depth to which the lodes may descend is limited by the thickness of the containing rock. But where the

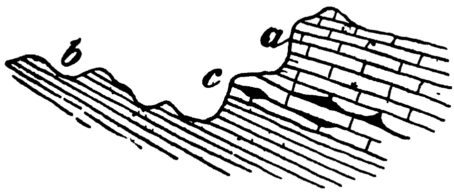


FIG. 239.—Showing gash-vein in limestone at Wangapeka, New Zealand.
(*a*) Silurian limestone. (*b*) Silurian slate.
(*c*) Gash-veins, with galena and blende.

original fissures pass down through the crust without regard to the character or number of the rock-formations, the lodes may descend to depths far beyond the limits of deep mining (fig. 240).

Length of Lodes.—Lodes may vary from a few hundred feet to scores of miles in length. In Cornwall, the average length of the lodes is about a mile; in Saxony, three or four miles; in the Harz Mountains, eight or ten miles.

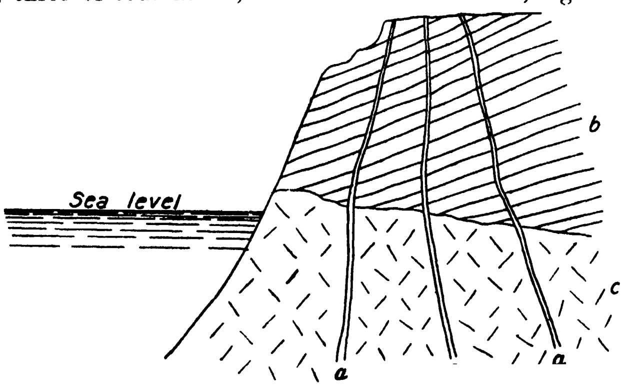


FIG. 240.—Lodes of Botallic Mine, Cornwall.
(*a*) Lodes. (*b*) Slaty shales. (*c*) Granite.

The Asch Lode in the Bavarian Forest can be traced for 25 miles; the Bohemian Pfahl, 34 miles; and the Great Pfahl, 92 miles.

The Mother Lode of California extends through five counties, being traceable for a distance of 70 miles.

Width of Lodes.—Lodes may vary in width both along their course and in depth. The same lode may vary from a mere clay parting to hundreds of feet in width. The celebrated Comstock Lode, Nevada, varies from 20 to 300 feet wide. The Great Pfahl, the most colossal quartz-lode in the globe, maintains an average width of 100 feet, but in places widens out to 370 feet.

Most great lodes occupy fault-fractures. The three gigantic lodes of the Bavarian Forest are regarded by Suess as the greatest monuments of linear dislocation in Europe.

Age of Vein-Filling.—In the case of veins and lodes traversing sedimentary and metamorphic rocks, it is natural to suppose that the formation of the ore-bodies would follow the periods of great orogenic movements, two of which are specially notable in geological history, namely, the late Carboniferous and the Middle Cainozoic. Both were characterised by extraordinary volcanic activity and igneous intrusion.

The uplift and intense folding of great segments of the earth's crust cause the formation of powerful fractures, which afterwards became channels for the circulation of mineral-bearing waters.

If a lode traverses a pile of strata ranging in age from the Silurian to the

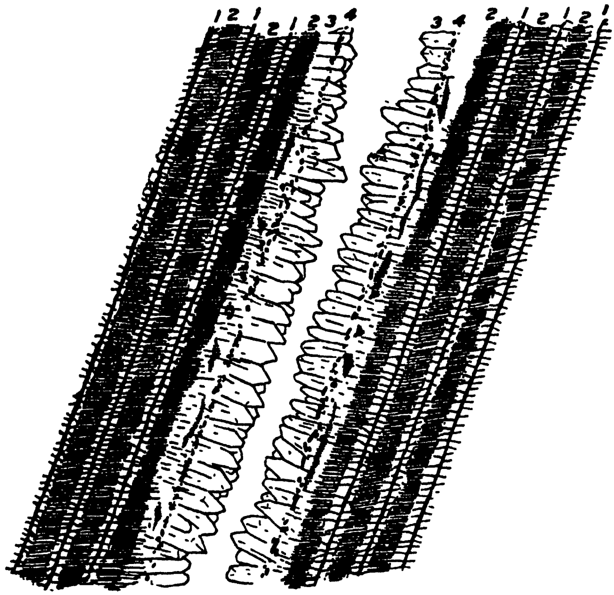


FIG. 241.—Showing comb-structure of lode-matter. Section showing arrangement of ore in vein.

1, Quartz, with galena and zinc blende. 3, Vug quartz.
2, Country-rock. 4, Iron pyrite disseminated through quartz.

Jurassic, it is obvious that the age of the lode-matter must be post-Jurassic. And if the Jurassic strata are overlain by an Eocene formation which the lode does not penetrate, then we know that the age of the lode is post-Jurassic and pre-Eocene—that is, Cretaceous.

In the Hauraki, Cripple Creek, Tonopah, Goldfields, and some Transylvanian mining areas, the gold-bearing veins are confined to andesitic lavas and tuffs of Middle Tertiary age. The veins occupy contraction cracks, and their filling must have taken place in late Tertiary times. Such veins are called *Propylite* veins, to distinguish them from *Tectonic* veins, which occupy cracks and cavities formed by crustal folding. *True veins* are profound fractures passing from one formation to another; and *Saddle-reefs* are typical examples of the tectonic type of ore-body.

Distribution of Valuable Contents in Lodes.—The matrix or gangue of most metalliferous lodes is quartz, but it is seldom that the valuable ore is equally distributed throughout the whole mass of vein-stone. Usually it occurs in

isolated ***bunches***, ***nests***, ***patches***, ***pockets***, or ***pipes***, to which the general term ***pay-shoot*** is frequently applied.

The pay-shoot or commercially valuable ore may occur on the ***foot-wall***, ***hanging-wall***, or middle of a lode, the remaining portion of which may be barren or too lean to be profitable. Or it may occupy the full width of that portion of the lode in which it occurs.

Influence of Country-Rock.—Frequently a lode, when it passes from one kind of rock to another, ceases to be profitable, or the converse. Moreover, a lode which yields lead and zinc where it traverses limestone, may contain copper in slates and tin in granite.

It is well recognised by miners that certain rocks favour the occurrence of particular metals and minerals. Thus tin has a preference for granite and granitic rocks; copper and chrome for serpentine; lead, zinc, silver, and iron for limestones and calcareous rocks.

Among sedimentary rocks gold has a preference for ancient sandstones and slates, and among igneous rocks for andesites of older Cainozoic date.

In a general way tin, tungsten ores, and gold have a preference for acidic rocks; and chrome, nickel, cobalt, iron, copper, and platinum for basic rocks.

Paragenesis.[1]—The genetic processes which have led to the formation or deposition of metal and minerals in ore-bodies have frequently brought about the association of certain minerals with one another.

Thus tin and wolfram are constant companions, also lead and zinc, gold and quartz, cobalt and nickel, iron and copper (as sulphides), chrome and serpentine.

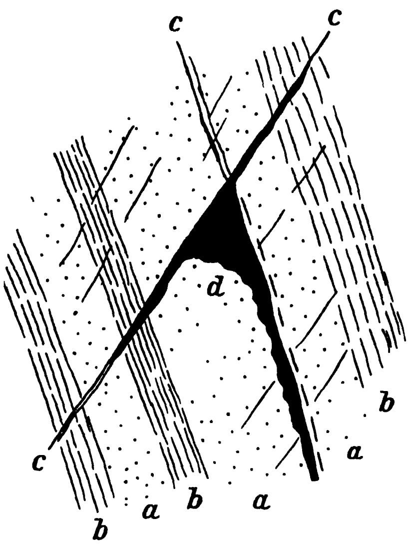


Fig. 242.—Showing formation of ore-body at intersection of joint planes, Bendigo Goldfield, Victoria. (After T. A. Rickard.)

Secondary Enrichment of Veins.—Sulphide ore-bodies, which crop out at the surface in non-glaciated regions, usually consist of two distinct portions, namely, the *oxidised zone* or *zone of weathering*, and the *unoxidised zone*, which generally lies below water-level (fig. 242A).

The oxidation of the upper portion of the lode is due to the action of rain-water, usually called *meteoric* water. The depth to which the alteration may extend is dependent on local topographical conditions and may vary from a few feet to 200 or 300 feet.

Mining operations have shown that most oxidised sulphide ore-bodies contain abnormally rich ore in the oxidised zone, frequently in the lower portion of it. This rich ore is supposed to arise from the migration of the valuable metallic contents from the higher portion of the vein to the lower portion through the agency of meteoric waters. In some cases the processes of dissolution, migration, and deposition of the ore may have taken place over and over again, each cycle resulting in a greater concentration of the valuable portion of the ore.

Secondary enrichment may also arise through the removal of the worthless metals, thereby leaving the valuable ore in a purer form.

[1] Gr. *para*=along side of, and *genesis*=birth.

The metals held in solution by permeating waters may be deposited as secondary sulphides on the primary sulphides in the lower portion of the lode. This is conspicuous in the Mount Lyell and Rio Tinto sulphide ore-bodies.

The first operation in the process of secondary enrichment is the chemical weathering and oxidation of the sulphides in the zone of weathering. The surface waters, now charged with minerals in solution, descend through the body of the lode and deposit their valuable contents in a concentrated or purer form through chemical or electrolytic action.

Metasomatic Replacement.—Till the beginning of the present century it was commonly believed that ore-deposits merely filled pre-existing fissures and cavities in country-rock. In recent years more or less stress has been placed on what has been called *metasomatic replacement.*

According to this, it is surmised that, in many cases at least, no previous cavities existed, but that the waters percolating through the rocks dissolved certain tracks or zones which they replaced with ore-matter and gangue.

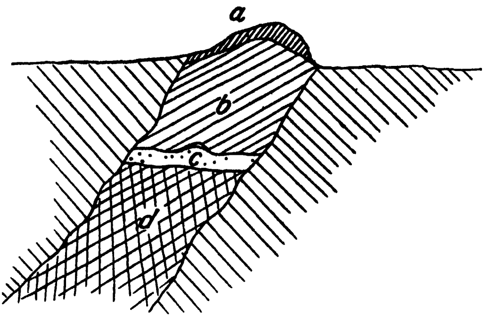


FIG. 242A.—Showing Zones of Oxidisation and Secondary Enrichment.

(*a*) Ironstone cap or *gossan*. (*b*) Zone of oxidised ore.
(*c*) Zone of Secondary Enrichment. (*d*) Primary sulphides.

This process of replacement has taken place among the constituents of many rock-masses, no matter how dense, including all metamorphic rocks, and all older igneous masses.

It is known as metasomatism (meaning change of body), and is due to internal chemical reactions, which seem to take place as readily in rocks as do the metabolic changes in living organisms.

In many cases minerals are replaced molecule by molecule, giving rise to what is termed mineral pseudomorphism. But in the processes which affect changes in rock-masses, reactions are set up between the different constituent minerals, thereby forming new minerals capable of segregating themselves into masses of all sizes.

Gneiss and mica-schist are familiar examples of the work of segregation and molecular rearrangement of the dominant constituents of altered sedimentary rocks. Such alteration is called metamorphism.

The internal changes that take place in igneous rocks are brought about by the breaking up of the primary silicates, followed by the production of secondary minerals. The processes concerned in these changes are mainly dependent on the chemical activity of water and aqueous vapours, possibly supplemented by the presence of gases. In most, if not all cases, the secondary minerals occupy a larger space than the original minerals; and from this we learn that their formation must have produced powerful disrupting stresses in the rock-mass. In rocks near the surface these stresses would find expression in

[To face page 454

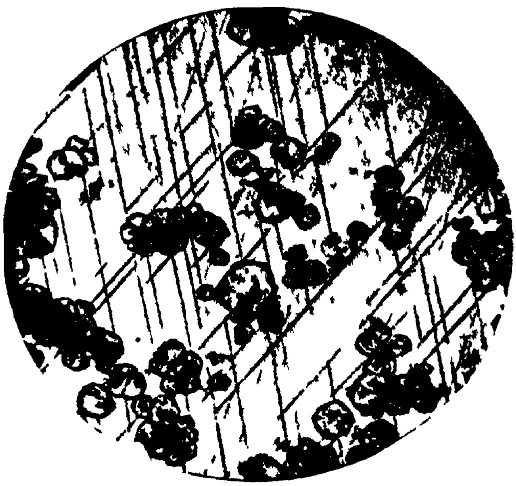


Fig. 243.—Showing iron and copper pyrites intergrown with garnets.

fracturing and faulting, and in deep-seated rocks in folding and plication as so often seen in gneiss, mica-schist, and other metamorphic rocks.

Besides these changes, which are chiefly molecular, rock-masses, and especially igneous rocks, may be so altered by the action of circulating waters as to bear no resemblance to the original rock.

In many cases andesites have been changed to propylite by the removal of certain essential constituents and the substitution of others.

Metasomatic replacement, as defined by Van Hise [1] and Emmons,[2] does not necessarily imply a mere substitution of matter, molecule for molecule, as happens in the process of pseudomorphism, which involves the preservation of the original form of the substance replaced, but an interchange of substance, the dissolved rock being replaced by grains or crystalline aggregates of one or more minerals.

Metasomatism is merely another name for certain types of rock-replacement or *mass-alteration*, and the chief processes by which this is brought about are—

(*a*) Carbonation.
(*b*) Dolomitisation.
(*c*) Silicification.
(*d*) Propylitisation.
(*e*) Regional Metamorphism.

Field observation and laboratory experiments show that practically all minerals are attacked by water and carbonic acid. The minerals of the augite and hornblende groups yield most readily to aqueous dissolution, then follow the plagioclase felspars, and after them orthoclase and the micas, with muscovite the most resistant of all. Among the commoner accessory minerals apatite is the most easily decomposed. Magnetite is less attacked, while corundum, chromite, and ilmenite, being most insoluble, accumulate in sandy residues.

Propylitisation.—In 1868 von Richthofen adopted the distinctive term "propylite" for the grey altered ore-bearing rocks of the Comstock lode, a name which was subsequently adopted by the United States Geological Survey.

In 1876 the result of Zirkel's microscopic examination of the North American rocks was published, and in this work he endeavoured to justify the retention of the term propylite as a distinct type of rock, although he went so far as to admit its association with the Tertiary lavas. In the following year Rosenbusch refused to accept propylite as a distinctive type of rock, but classed many rocks known as such with the andesites.

In 1879 Doelter showed that the Hungarian rocks, which possessed the features held by von Richthofen and Zirkel to be characteristic of the propylites, could be seen to pass insensibly, by a gradual process of alteration, into ordinary andesites. Shortly after this Doelter's view was strongly upheld by Rosenbusch, and in the same year Wadsworth very forcibly insisted that the distinction between the propylites and andesites could not be maintained in the case of the North American rocks.

In his *Geology of the Comstock Lode and Washoe District*, 1882, G. F. Becker states that the grey altered ore-bearing rock, which corresponds with the "kindly country" of the Hauraki goldfields, could not be regarded as a distinct group of rocks, but only as a distinct *facies* or habitus of the andesitic lavas. The microscopic examination of a large number of the rock specimens obtained in the deepest workings and during the construction of the Sutro

[1] Van Hise, *16th Annual Report U.S. Geol. Survey*, part i., p. 689.
[2] S. F. Emmons, *U.S. Geol. Survey*, Monograph xii., p. 565.

tunnel enabled Becker to show that, by the gradual alteration of their constituent minerals, the hornblende and augite-andesites gradually acquired those characteristics which had been held to be peculiar to the propylites.

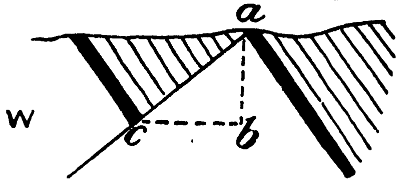


FIG. 244.—Showing displacements caused by strike-fault.
(a-b) Vertical displacement of throw. (b-c) Horizontal shift.

In 1886 Rosenbusch accepted the term propylite, not, however, as indicating a distinctive group of rocks as originally contended by Richthofen and Zirkel, but only as a convenient name serving to distinguish a well-marked and interesting pathological variety of the andesitic type of rock. There seems

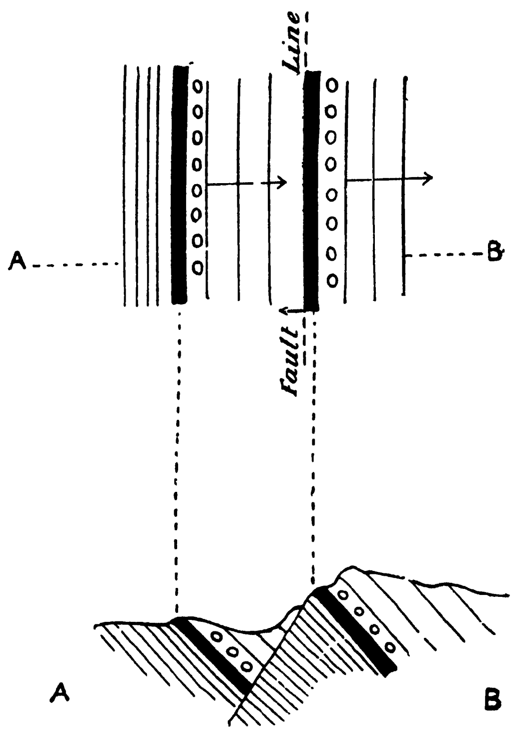


FIG. 245.—Showing repetition of coal-seam by strike-fault.

to be no good reason why the term should not be used in the restricted sense suggested by Rosenbusch.

The typical propylites are compact grey rocks in which the hornblende and biotite are altered into green chloritic products, while the felspars are completely kaolinised and have given rise to colloidal silica, calcite, and epidote. Iron pyrites in minute crystalline specks is abundantly disseminated throughout the rock.

At the Thames and Waiki goldfields the andesites are known to be altered to a depth of 1500 feet below sea-level. How much deeper the alteration extends has not yet been ascertained. It is significant that the propylitisation is confined to the neighbourhood of the old volcanic centres of eruption. Beyond these centres the andesites exhibit the ordinary effects of weathering by the processes of hydration and oxidation.

Deep-seated propylitisation has been brought about by pneumatolytic agents supplemented by thermal waters charged with carbonic acid. The gold and

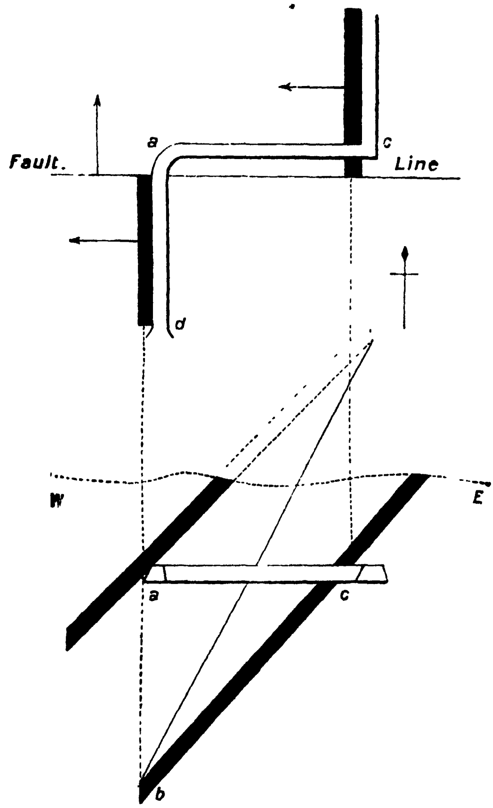


FIG. 246.—Showing effect of dip-fault.

silver veins that frequently occur in propylites were apparently formed by hydrothermal action in the later or expiring phase of volcanic activity, and represent local concentrations of silica and ores in contraction rents and fault-fractures.[1]

Brecciated Lodes.—Wall-movements of considerable magnitude have taken place on the course of many lodes, whereby the gangue has become crushed and broken. Subsequently when re-cemented by infiltration, such crushed lode-matter is said to be brecciated.

Faulting of Lodes.—Lodes and bedded mineral deposits may be intersected by faults, which may run parallel with the strike or at right angles to it.

Strike-faults (figs. 244, 245) cause vertical and horizontal displacements of the veins or seams they intersect.

[1] On question of propylite, see M. E. Wadsworth, *Proc. Bost. Soc. Nat. Hist.*, 1883, pp. 416–417; and Prof. Judd, *Quart. Journ. Geo. Soc.*, vol. xlvi., 1890, pp. 341–382.

Strike-faults also cause a repetition of the seam or vein at the surface.

Dip-faults (fig. 246) produce an *apparent* lateral displacement of the beds or veins which they cross. When the faulting takes place, the principal movement is a vertical one. Consequently, when the vein is vertical, the severed ends merely slide on one another.

The apparent *heave* or lateral displacement is produced by the denudation of the elevated portion causing the outcrop to recede in the direction of the dip as shown in figs. 95 and 96. The flatter the dip, the greater will be the apparent lateral displacement.[1]

Ores and Minerals Genetically Considered.

The constant association of ore-deposits and igneous rocks has led to the broad generalisation—*That ore-deposits are genetically connected with the eruption of igneous magmas.*

Three stages of ore-formation that originated by igneous intrusions may be recognised—

1. Magmatic.
2. Pneumatolytic.
3. Hydrothermal.

In the magmatic stage the ore-minerals, mainly oxides, are among the first to separate from the molten magma. In the pneumatolitic stage, which is distinguished by the copious emanation of gases and aqueous vapour, the magma becomes consolidated but is still intensely hot. The gases and vapours permeate the whole mass and attack the primary silicates, which may be broken up and altered, or in some cases completely replaced by ore-minerals. In the hydrothermal stage the intrusive rock has sufficiently cooled to permit the condensation of the magmatic aqueous vapour. The alkaline *juvenile* water thus formed is usually metal-bearing and silica-laden, and hence it deposits ore-minerals in all the cracks and open fissures it is able to penetrate. It may also react on the ore-minerals deposited during the preceding stages, and in this way effect a secondary concentration.

The magmatic, pneumatolytic, and hydrothermal stages in the history of an igneous intrusion pass insensibly into one another, and as the ore-forming processes were in operation from first to last it may, in some instances, be difficult to distinguish an ore-deposit as magmatic or pneumatolytic or hydrothermal. The extreme forms of each stage are easily identified.

Genetic Classification of Ore-Deposits.

The genetic classification that satisfies most nearly our present knowledge relating to the origin of ores and minerals comprises five classes as follows :—

I. Magmatic segregation.
II. Eruptive after-actions :
 (*a*) Pneumatolytic :
  (1) Contact ore-deposits, and (2) bed-impregnations in neighbourhood of contacts and fissures.
 (*b*) Hydrothermal :
  Most ore-bodies occurring as veins and lenses.
 (*c*) Fumarolic :
  Sulphur and boron deposits.

[1] The recovery of faulted lodes and coal-seams by graphic projection is fully described in Park's *Mining Geology* (Charles Griffin & Co., Ltd.).

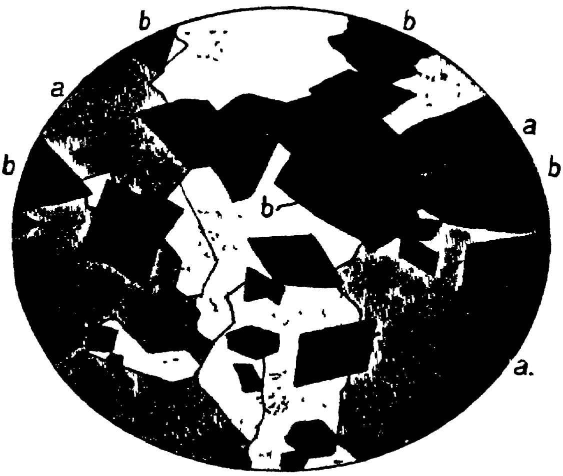


FIG. 247.—Showing structure of pyritic quartz in thin section, U.S. Geol. Survey. (After Lindgren.)

(*a*) Quartz. (*b*) Arseno-pyrite.

III. Dynamical or Metamorphic:
Ore-deposits that occur in metamorphic rocks, such as gneiss, mica-schist.

IV. Meteoric waters:
(*a*) Chemical deposits.
(*b*) Mechanical deposits.

V. Organic:
(*a*) Vegetable deposits.
(*b*) Animal deposits.

I. MAGMATIC SEGREGATION.

Ore-bodies of this class consist of metals and ores that have separated from the magma as primary constituents; hence they occur not as great concentrations but mostly as grains or as small masses scattered throughout the parent rock. Ore-accumulations resulting from rock-alteration by pneumatolytic processes, or those formed by hydrothermal action, are not to be classed as magmatic deposits. Though related to magmatic separations, they owe their origin to the after-actions that follow the magmatic period. Magmatic ore-segregations mark the beginning of ore-forming processes; hence when viewed in the broader sense they may be regarded as merely sporadic rock types.[1]

Modern geologists have abandoned the old conception of the Earth's interior condition, which postulated the existence of an enormously compressed *liquid molten mass of high specific gravity charged with heavy metals. The composition of the molten magmas that have issued at the surface, in successive geological ages, does not favour any hypothesis which assumes the existence of* a greater proportion of the heavy metals in the barysphere than in the upper crust or lithosphere.

The petrographical researches of Vogt and Brögger disclosed in basic dykes a tendency of the heavy minerals to segregate near the borders. The occurrence of massive mineral aggregates near their borders is a marked characteristic of peridotites, serpentines, and all the ultra-basic eruptives.

For physico-chemical reasons, ore-segregations are more common in basic and ultra-basic rocks than in acidic rocks.

Classification of Magmatic Ores.—According to their composition, magmatic ores may be divided into two groups—

(1) Oxide ores.
(2) Ores of the native metals.

The oxide group includes magnetite, ilmenite, chromite, and corundum; the second group, nickeliferous iron, copper, platinum, and perhaps gold. Ilmenite and magnetite occur in igneous rocks as disseminated grains, and do not form deposits of economic value. Chromite and corundum occur as disseminated grains, and as massive aggregates that are in some cases commercially valuable.

The native metals that comprise the second group occur in the parent rock as disseminated grains; but nowhere has the rock proved rich enough to be worked profitably for the contained metal. The world's supply of platinum is obtained from sands derived from the denudation of platinum-bearing ultrabasic igneous rocks.

[1] T. Crook, "The Genetic Classification of Rocks and Ore-Deposits," *Mineralogical Mag.*, xvii. p. 55, 1914.

Except magnetite and ilmenite, magmatic ores occur only in basic eruptive rocks. Thus we find—

(*a*) Chromite in peridotite and serpentine.
(*b*) Magnetite and ilmenite in basic and semi-basic eruptives.
(*c*) Copper and nickel-iron in serpentine.
(*d*) Platinum metals in highly basic eruptives.

Chromite in Peridotite.—In the South Island of New Zealand there are two masses of peridotite that form bold mountain peaks in which the magmatic segregation of chromite is strikingly exhibited.

A few miles from the city of Nelson, Dun Mountain rises to a height of over 4000 feet above sea-level. It covers an area of about four square miles, and is composed of massive olivine,[1] in which chromite of iron is uniformly disseminated in the form of fine grains.

The adjacent rocks are argillite and limestone of probably Permo-Carboniferous age, the limestone occurring at the base of the sedimentary formation. Between the limestone and the olivine, to which Hochstetter[2] gave the distinctive name dunite, there is a belt of serpentine half a mile wide.

The serpentine contains lenticular-shaped masses of chromite, native copper, and copper ores, principally chalcopyrite. It also contains thin irregular veins of diallage, bronzite, enstatite, scapolite, wollastonite, and chrysolite. The larger masses of chromite in the serpentine occur along the limestone contact.

The second great mass of dunite forms Red Mountain, situated 20 miles north of Milford Sound in Otago.[3] It is over 6000 feet high, and covers an area of about ten square miles.

The mountain is composed of olivine and chromite. The latter occurs in much greater proportion than at Dun Mountain. The peridotite is flanked on two sides by belts of serpentine, which separate it from the adjacent argillites and sandstones of Palæozoic Age.

The massive aggregates of chromite that have been mined at Dun Mountain and Little Ben, Nelson, occur in serpentine. The serpentine itself is an alteration product of the dunite. Throughout its mass it contains no grains of chromite; hence it seems not improbable that the bodies of chromite that occur in it are not magmatic but the result of secondary aggregation.

Nickel-Iron.—This rare alloy was known to exist in many meteorites long before it was discovered to be a constituent of the rocky crust of the earth.

The sands in the streams that drain the Red Mountain serpentine area yield small quantities of the nickel-iron alloy, Awaruite, first distinguished by Skey in 1885.[4]

It has since been found *in situ*, in the serpentine of Barn Bay, near Red Mountain.[5]

A nickel-iron alloy, the same as or related to Awaruite, has been found in gold-bearing sands at the River Biella, Piedmont, associated with chromite separated from peridotite[6]; in serpentine in Josephine County, Oregon[7];

[1] J. H. L. Vogt, "Problems in the Origin of Ore Deposits," *Genesis of Ore Deposits*, 1901, p. 639.

[2] Dr. F. von Hochstetter, *Zeitschrift der deutschen geol. Gesells.*, xvi. p. 341, 1864.

[3] J. Park, *New Zealand Geological Reports and Explorations*, 1886–87, p. 121.

[4] W. Skey, *Trans. N.Z. Inst.*, vol. xxiii. p. 401, 1885.

[5] G. H. Ulrich, "On the Discovery, Mode of Occurrence, and Distribution of the Nickel-iron Alloy Awaruite on the West Coast of the South Island of New Zealand," *Quart. Jour. Geol. Soc. London*, vol. xlvi. pp. 619–632, 1890.

[6] *Comptes Rendus*, vol. cxii. p. 171.

[7] *Am. Jour. Sci.* (4), vol. xix. p. 319, 1905.

in sandstone, associated with chromite, in Fraser River, British Columbia [1]; and in Smith River, Del Norte County, California.

Native Copper.—The association of copper and chromite in serpentine at Dun Mountain has already been mentioned. Native copper is found in serpentine in Cornwall, in New South Wales, and many other parts of the globe. Large masses of native copper, associated with silver, are found in amygdaloidal diabase at Lake Superior. The magmatic origin of these masses of metal has not yet been satisfactorily proved. They may have been deposited in shrinkage cavities by electro-chemical action, the concentration of the metals having been effected by the action of heated waters.

Platinum Metals.—Platinum has rarely been found in the matrix *in situ*, and then only in basic or ultrabasic rocks. In the Ural Mountains it occurs as grains in peridotite and serpentine.

The bed-rock of the Vyzaj and Kaiva rivers, on the western flanks of the Urals, consists of olivine-gabbro, containing disseminated grains of platinum, but not apparently in payable quantity. An olivine rock was discovered in 1893 at Goroblage-datsk, on the western side of the Urals, containing chromite and platinum, the latter at the rate of 14 dwt. 9 gr. to the ton of rock. Carmichael,[2] in 1902, reported the occurrence of platinum in fine-grained dark basaltic rock.

Platinum occurs in a peridotite resembling dunite in the Sierra Ronda, which extends along the Mediterranean coast from Gibraltar to Malaga in Spain.[3]

Sulphides not Magmatic.—On account of their occurrence in igneous rocks, Prof. Vogt[4] classified the Sudbury and other nickeliferous sulphide ores as magmatic separations. There are physico-chemical reasons for believing that sulphide ores can never be primary constituents of any igneous rock. The aqueous vapours and gases with which magmas are charged are powerful oxidisers. Hence the early crop of iron and alumina minerals are oxides; and it seems opposed to our knowledge of chemical reactions to find these oxides co-existing with sulphides in a cooling magma. The recent investigation of the Sudbury ores by Tolman and Rogers[5] appears to show that the sulphides are of secondary and not of primary origin.[6]

The rich nickeliferous sulphide at Creighton, Sudbury, is a lens of arc resembling in shape a puckered piece of green bullock's hide or the human ear turned upside down. The varying relationships of this ore-body to the associated norite, granite, and greenstone would tend to show that it is a typical contact-deposit.

II. ORES FORMED BY ERUPTIVE AFTER-ACTIONS.

It is manifest that the eruptive after-actions will begin at the moment of intrusion of the magma, and continue till the rocks have become completely cooled.

[1] *Loc. cit.*, p. 319.

[2] *Eng. and Min. Jour.*, New York, Feb. 12, 1902.

[3] *Comptes Rendus*, vol. clxii. pp. 45–46, 1916.

[4] J. H. L. Vogt, *Zeit. f. prakt. Geol.*, 1893, pp. 4–11, 125–143, 257–284; *ibid.*, 1894, pp. 381–399; 1900, pp. 233–242, 370–382; 1901, pp. 9–19, 180–186, 289–296, and 327–340.

[5] C. F. Tolman, jun., and Austin F. Rogers, *A Study of the Magmatic Sulphide Ores*, Leland Stanford Junior University Publications, University Series, 1916, pp. 1–76.

[6] The views of C. W. Knight, E. Howe, A. F. Coleman, N. L. Bowen, V. Zeigler, W. L. Uglow, F. J. H. Merrill, F. C. Calkins, A. Knopf, E. S. Bastin, A. L. du Toit, W. H. Goodchild, A. G. White, and others, are discussed, with references given, in *Text-book of Mining Geology*, Chas. Griffin & Co., Ltd., London, 4th ed., 1918, pp. 182, *et seq.*

Igneous magmas contain more or less water, together with many constituents of a hydrous or gaseous character. Hence the fusion of magmas is not believed to be pyrogenetic, that is, the result of dry heat alone, but hydatopyrogenetic, that is, fusion by heat, in the presence of water.

According to Arrhenius,[1] water renders the magma more liquid. It has been shown by experiment that magmas which require a temperature of 3000° F. to produce dry fusion, can be fused in the presence of water at 500° F. Further, it has been shown that the presence of water aids in giving a magma fluidity. Barus [2] was able to fuse glass at 200° C. in the presence of water.

Arrhenius believes that water, in a magma, acts the part of an acid, liberating free silicic acid and free bases.

The activity of water at high temperature is very great. Barus [3] has shown that water, heated above 185° C., attacks the silicates composing soft glass with remarkable rapidity; and Lemberg has proved, experimentally, that water, at a temperature of 210° C., slowly dissolves anhydrous powdered silicates. It is probable that, at great depths, the pressure will be sufficient to hold the water in the form of a liquid, in a superheated condition.[4] At high temperatures both water and steam possess a great capacity for dissolving mineral substances. They may thus become important mineralisers.

Contrary to the common belief, Oetling [5] asserts that when a magma is once molten the pressure of 200 or 300 atmospheres tends to keep it molten longer than in ordinary conditions.

(*a*) **Pneumatolytic Ore-Deposits.**—Two main types of pneumatolytic ore-deposit are recognised—

(1) Contact ore-deposits and rock-impregnations in the neighbourhood of the contact.

(2) Bed-impregnation.

Contact-Deposits.—A molten magma tends to effect changes in the rocks with which it comes in contact. In the case of overflow magmas, the thermal changes are usually trifling, and in many cases hardly appreciable. Even magmas that have cooled in rents in sedimentaries at shallow depths have not always caused great changes in the enclosing rock. The greatest alteration will, naturally, take place in the case of magmas that do not reach the surface, but cool slowly under great pressure. The greater the mass of the intrusive magma, the slower will be the rate of cooling; and the slower the rate of cooling, the longer will the adjacent rocks be heated.

The rate of cooling will be mainly dependent upon the mass of the intrusion, the distance from the surface, and the relative thermal conductivity of the adjacent rocks.

The changes effected in the country-rock by the intrusion of an igneous magma will be mechanical, thermal, and chemical. The mechanical stresses will fracture and deform the rocks invaded by the magma; while the heat of the magma will bake and dehydrate the rocks that come within its influence. The gases and aqueous vapours arising from the dehydration acting in concert with the magmatic gases and vapours will cause a molecular rearrangement of many of the rock constituents, thereby generating additional stresses.

[1] Svante Arrhenius, "Zur Physik des Vulkanismus," *Geol. Fören. Förh.*, Stockholm, 1900.

[2] C. Barus, *Am. Jour. Sci.*, vol. vi. p. 270, 1898.

[3] C. Barus, "Hot Water and Soft Glass in their Thermo-dynamic Relations," *Am. Jour. Sci.* (4), vol. ix. p. 161, 1900.

[4] C. R. Van Hise, "Some Principles controlling the Deposition of Ores," *Trans. Am. Inst. Min. Eng.*, vol. xxx. p. 27.

[5] *Tschermaks, Min. u. petrog. Mitth.*, vol. xvii., 1897, p. 33.

Mineral replacement arising from these agents will also set up disrupting stresses.

Contact-Metamorphism is due to the heat of the molten magma combined with the action of the aqueous vapour and gases expelled from it during cooling. It is well known that during and following volcanic eruptions, water, hydrogen sulphide, sulphur dioxide, and carbon dioxide, as well as compounds of chlorine, fluorine, and boron, are emitted. While some of these may result from the contact of the magma with the intruded country-rock, it is probable that the greater portion of them is magmatic. The intruded sedimentaries will be compressed, bent, and more or less shattered and fissured along the line of intrusion. The magma will part with its heat by slow radiation into the adjacent rocks The occluded steam and gases in the magma, together with the steam generated from the water contained in the sedimentaries, will pass into and permeate the latter, and cause a molecular re-arrangement of the constituent minerals, resulting in what is called contact-metamorphism.

As the igneous magma and the heated sedimentaries cool, they will contract in mass, and when the temperature normal to the depth has been reached, the contraction will tend to cause the two rocks to shrink from one another, resulting in the formation of cavities along the line of contact

The contraction or decrease in volume of a molten magma in solidifying, according to the experiments of Barus,[1] Forbes,[2] Delesse,[3] and Cossa,[4] varies from 4 or 6 per cent. of the original volume.

Above a temperature of 365° C., and a pressure of 200 atmospheres, water, and all more or less volatile compounds, will exist as gases. Aqueous vapours above the critical temperature and under great pressure will react as strongly upon the cooling magma as upon the adjacent rocks. They will possess a solvent power, that will be greatest where the highest temperature and pressure exist. The pressure will cause the heated steam and gaseous emanations carrying the heavy metals to permeate the bedding planes of the invaded rocks, and fill all accessible cracks and fissures. In this way bed-impregnation may be effected, and even ore-bodies formed at points some distance from the eruptive magma.

A decrease in the temperature and pressure will permit the least soluble substances to be deposited first; and as the temperature and pressure continue to diminish the dissolved substances will be thrown out of solution in the inverse order of their solubility.

It is manifest that the later phase of the eruptive after-actions will represent, in a modified form, the waning effects of hydrothermal action. The deep-seated conditions will also favour the action of metasomatic processes in the zone of anamorphism, and veins will be formed, some of which may reach the surface.

It is probable that the circulation of the heated mineralised solutions, in the later phases, will tend to effect a redistribution of the ores and minerals deposited in the earlier stages. In some cases the ascending waters and gases may reach the zone of surface circulation and mix with the meteoric waters, which may then reappear as hot springs, forming ore-bodies and veins not directly in contact with the eruptive magma. Obviously such ore-bodies will be noted for their persistence in depth.

Weed and some other writers have made an attempt to subdivide contact-

[1] Barus, *Phil. Mag.* (5), vol. xxxv. p. 173, 1893.
[2] Forbes, *Chem. News*, Oct. 23, 1868.
[3] Delesse, *Bull. Soc. géol. France* (2), vol. iv. p. 1380, 1847.
[4] Zirkel, *Lehrbuch d. Petrographie*, vol. i. p. 681, 1894.

deposits into groups, depending mainly on their mode of occurrence. Clearly the form and mode of distribution may be due to accidents of density or porosity, composition, and hydrous condition of the rocks affected, rather than to differences in the genetic processes. Moreover, the mass of the magma, the weight of superincumbent rocks, the amount of heat and subsequent contraction, and phase of the after-action, are doubtless contributing factors in determining the form and distribution of the valuable ores.

Masses of ore, occurring as contact-deposits, true veins, and bed-impregnations, in the zone of alteration may all be traced to the same genetic cause.

L. de Launay supports the view of the school of De Beaumont and Daubrée in respect of the primary influence of volatile mineralisers emanating from eruptive magmas. The emanations, he contends, must have prepared the way, by introducing into the enclosing rocks, or simply by depositing in the vein-fissures, constituents such as sulphides, fluorides, chlorides, etc., which, subsequently dissolved anew by the circulation of superficial waters, have rendered the latter essential aid in the processes of alteration.[1]

The extent of contact-metamorphism effected by the granite intrusions of Albany, in New Hampshire, was fully investigated by Hawes.[2] His analyses show a progressive series of changes in the schists as they approach the granite. The rocks are dehydrated, boric and silicic acids have been added to them, and there appears to have been an infusion of alkali at the time of contact. He concluded that the schists had been impregnated by hot vapours and solutions that emanated from the granite.

It has been suggested by Lindgren that one of the thermal effects of an igneous intrusion would be to render the adjacent rocks granular and porous, whereby steam and gases would be enabled to permeate rocks that were otherwise impenetrable, in the same way that a raw brick of clay becomes granular and porous after being burnt in a kiln. The obvious objection to this view is that the thermal effects of an igneous intrusion are nearly always confined to a thin skin of rock along the contacts. The baking and granulation is usually local, and probably in every case insignificant when compared with the area affected by ore-impregnation. This is noticeably the case in respect of tin-impregnations.

Contact-deposits generally lie at the boundary between the eruptive and the country-rock; but they may also occur at a considerable distance from the eruptive, but never outside the zone of alteration.

More particularly contact-ores occur in limestones, marls, and clay-slates, and are accompanied by the usual contact-minerals, garnet, vesuvianite, scapolite, wollastonite, augite, mica, hornblende, etc., and in clay-slate by chiastolite, etc.

The most common contact-ores are magnetic and specular iron, but sulphides of copper, lead, and zinc often occur.

Pyritic contact-deposits are typically represented by those of Vigsnäs, in Norway, Rio Tinto, Tharsis, and San Domingo, in Spain.

The pyritic ore-mass at Mount Lyell, Tasmania, is usually described as a replacement contact-deposit, although its geological occurrence does not strictly conform to the common definition of such a body. Gregory describes it as a boat-shaped mass, lying between talcose schist and conglomerate.[3] The mine-workings have shown that it gradually tapers downwards from the

[1] L. de Launay, *The Genesis of Ore Deposits*, 1901, Discussion, p. 616.
[2] G. W. Hawes, *Amer. Jour. Sci.*, vol. xxi. p. 21, 1881.
[3] J. W. Gregory, "The Mount Lyell Mining Field," *Trans. Aust. Inst. Min. Eng.*, vol. i., part iv., July 1904, p. 281.

outcrop, being cut off with a rounded base by a great thrust-plane (*loc. cit.*). There are no eruptives in actual contact with the ore-body, but dykes of diabase and other igneous rocks occur in the district, at no great distance. The presence of these dykes, and of bands of schist, impregnated with sulphides, forming fahlbands, would lead to the belief that at one time there existed channels of communication leading from the eruptive magma to the vein-cavities. In all probability the Mount Lyell sulphide ore-bodies and bed-impregnations were formed in the later stages of eruptive after-actions.

(*b*) **Hydrothermal** (*i.e.* formed by thermal waters, aided by steam and gases).—As before mentioned it is well known that during and after volcanic eruptions there are emitted enormous volumes of steam, also hydrogen sulphide, sulphur dioxide, carbon dioxide, as well as compounds of chlorine, fluorine, and boron.

These gaseous and aqueous emanations come from the same source as the igneous magma, accompany the magma in its ascent, and may possibly be one of the contributing causes of the eruption.

The gold- and silver-bearing veins that traverse propylitised andesites, dacites, etc., in Hungary, Transylvania, Nevada, Colorado, and New Zealand,[1] belong to the hydrothermal type of vein. In a discussion on the rôle played by the waning forces of volcanic phenomena in the formation of ore-veins Suess [2] says: "Hot springs may be taken as the latest phase of a whole series which led up to the present deposits of ore."

(*c*) **Fumarolic.**—The deposits compressed in this sub-class are formed by the steam and gases that escape at the surface in volcanic regions. Of these the most important are deposits of sulphur, boron salts, ferric chloride, and cupric oxide; but of these sulphur and boric acid alone are of economic value.

Boron salts are common in the neighbourhood of many volcanoes. The entire production of boric acid from Italy is obtained from the steam fumaroles in the provinces of Pisa and Grosseto.

Sulphur is sublimed from fumaroles and craters by the mutual reaction of hydrogen sulphide and sulphur dioxide. It is found impregnating tuffs, and filling the cavities in lavas and siliceous sinters. It also occurs mixed with volcanic muds and gypsum deposits of volcanic origin.

The most important known deposits of sulphur occur in Italy, Spain, Hungary, Chile, Mexico, Japan, Texas, and New Zealand.

The sulphur deposits of Italy occur as veins and lenticular masses, in rocks of Miocene age, mostly in the provinces of Caltanisetta and Girgenti.

In Louisiana and Texas the sulphur occurs in the coastal plains, in the form of domes in a limestone formation that lies buried under from 450 to 800 feet of quicksand. The sulphur is liquified by superheated water and hot air, and then forced to the surface through a line of pipes.

III. DYNAMICAL.

Regional Metamorphic Deposits.—To this class belong the deposits of iron-ore that occur in altered sedimentary rocks, mostly of older Palæozoic Archæan age. Iron oxide ores are common as accessory constituents of many igneous rocks; but, as a rule, they occur as disseminated grains and hence are not commercially valuable.

Practically all massive deposits of iron-ore are of sedimentary origin formed in various ways. They may be divided into two great classes: (1) those that

[1] J. Park, *Text-book of Mining Geology*, London, 4th ed., 1918, pp. 198–209.
[2] E. Suess, "Lecture," *The Geographical Journal*, vol. xx., Nov. 1902, p. 520.

existed as ironstones in the rocks in which they occur, and (2) those produced by the alteration of limestones.

All natural surface waters contain iron in solution, chiefly as salts of the organic acids of the humic group. The deposition of ferruginous deposits in the form of bog iron-ore is always going on in swamps and certain shallow lakes where there is an accumulation of decaying vegetation. Much of the iron is feebly combined. In certain conditions it attaches itself to the carbonic acid of the atmosphere, and is precipitated as the carbonate, which soon becomes oxidised to hydrated oxides among which limonite is the most common. Another portion of the iron may be precipitated directly as hydrated oxide. By some, the oxidation is believed to be brought about by the action of bacteria or algæ. The iron oxides accumulate on the bottom of the swamps and lakes, and in time form sheets of great thickness. The *ironstone pan* of swamp- and fen-lands was formed in this way.

Iron oxides are a conspicuous constituent of all strata of continental origin, which are characteristically red or reddish-brown in colour. Beds of impure earthy ironstone consisting of varying proportions of carbonate and oxide ores occur as nodular bands and beds in the Carboniferous Coal-measures of Britain and Lower Tertiary measures of New Zealand. The former were of great extent and value. The origin of these ores is similar to that of modern bog-ores and lake-ores.

Some of the world's most valuable deposits of iron-ore have been produced by the alteration of limestones. In its simplest form this is brought about by the replacement of the calcium carbonate by ferrous carbonate, which is unstable and easily undergoes further oxidation to limonite. The limonite may be afterwards dehydrated to hæmatite, or partially deoxidised to magnetite. The valuable ironstones of the Jurassic system of the Midlands and Yorkshire, of Bilboa, Spain, and of the eastern States of America, belong to this class of iron-ores.

Some of the Archæan rocks of the Lake Superior region and of Sweden are rich in hæmatite and magnetite. The ore occurs as massive bodies and contact-deposits, the former interstratified with the crystalline rocks with which they are associated. The iron probably existed originally as a sedimentary bog-ore or lake-ore, and became concentrated and re-arranged by the processes that brought about the metamorphism of the enclosing rocks.

Massive aggregates of magnetite and specular iron are common in chlorite-schist, gneissic and quartzose schists in all parts of the globe, but only in a few regions do they exist in sufficient quantity to be of value for the production of iron.

Crystalline schists also enclose beds of iron pyrites and pyrrhotite, the origin of which is still obscure.

The iron-ores of the Mesabi district, in Minnesota, occur as shallow basin-shaped deposits that pass at the edges into ferruginous chert. For the most part, the deposits lie near the axes of gentle troughs in the Huronian rocks, but in many cases they are independent of the synclinal arrangement of the adjacent rocks.

According to Prof. C. K. Leith,[1] the ores have originated from the alteration and secondary concentrations, under surface conditions, of green ferrous silicate granules (greenalite).

He believes their development to have been analogous to that of the iron carbonates of other parts of the Lake Superior region. On the other hand,

[1] "The Mesabi Iron-bearing District of Minnesota," 1903, Monograph xliii., *U.S. Geol. Surv.*

Spurr[1] maintains that the green granules, notwithstanding the absence of potash, were originally glauconite.

In 1901 Prof. C. R. van Hise[2] announced his agreement with Leith's view that the green ferrous silicate minerals were not originally glauconite.

In 1902 Spurr[3] reaffirmed his belief in the organic (glauconitic) origin of the Mesabi iron-ores, and expressed the view that probably most of the Lake Superior iron-ores have a similar origin.

IV. METEORIC WATERS.

(*a*) **Chemical.**—In this group are included deposits of silt, borax, nitre, bog-iron ore, and some deposits of gypsum and manganese.

(*b*) **Mechanical.**—This group includes all sedimentary rocks formed by the agency of water in lakes and seas ; also alluvial drifts, whether loose or compact, of river or lake origin, containing gold, tin, platinum, and gems ; and ore-bearing sea-beach deposits.

V. ORGANIC.

(*a*) **Vegetable.**—This group embraces all varieties of mineral fuel, ranging from peat to anthracite, also graphite, oil-shale, mineral-oil, natural gas, and diatomaceous earths.

(*b*) **Animal.**—The minerals included in this subdivision are limestones, including chalk ; and mineral phosphates that originated from the leaching of guano and animal remains, and the secondary concentration of the phosphoric acid as calcium phosphate.

Theories of Vein-Formation.

The two theories which receive the most support are—

1. The Ascensional or Eruptive Processes Theory.
2. Lateral Secretion Theory.

Ascensional Theory.—According to this view, all ore-bodies and ore-veins owe their origin directly or indirectly to the intrusion of igneous magmas. The intrusive shatters the rocks and provides the metals which it brings up from the barysphere. The metals are expelled from the cooling magma in the form of highly-heated vapours which are deposited in the cracks and fissures in the neighbouring rocks. Moreover, the steam condenses and carries the metals upward through cracks and fissures which eventually become filled with mineral matter, thereby forming mineral veins. The alteration and replacement of the country-rock is also accelerated by the steam, gases, and heated waters emanating from the cooling igneous magma.

The almost constant association of ore-bodies and igneous intrusions gives powerful support to the Ascensional theory, which is now more favoured by mining geologists than any other.

Lateral Secretion Theory.—According to this view, it is assumed that meteoric waters percolating through the rocks, by the aid of carbonic acid and alkalies, dissolve out certain constituents, which are afterwards deposited in cracks, fissures, and cavities, thereby forming veins and ore-bodies.

[1] J. E. Spurr, *Am. Geol.*, vol. xiii , 1894, pp. 335–345.
[2] "The Iron-deposits of the Lake Superior Region," *Twenty-first Ann. Rept. U.S. Geol. Surv.*, part iii., 1901, pp. 351–370.
[3] *Am. Geol.*, vol. xxix., 1902, pp. 335–349.

In support of this view it is asserted that sedimentary and igneous rocks alike contain all the constituents formed in veins which are merely regarded as local concentrations.

It is well known that cracks in limestones soon become filled with calcite deposited by water slowly percolating through the body of the rock. Similarly, cracks and tension-rents in sandstones and igneous rocks become filled with quartz, calcite, pyrite, or other minerals, all of them obviously local concentrations of mineral matter derived from the surrounding rocks.

The frequent association of igneous intrusions and ore-bodies is admitted by the supporters of the Lateral Secretion theory; but they contend that the gases and steam emanating from the magma merely accelerate and supplement the action of the meteoric waters in the concentration of the metals which previously existed in the intruded rocks as primary constituents.

Summary.—The Lateral Secretion theory does not satisfactorily explain the formation of the large pyritic replacement ore-bodies; hence at present the Ascensional theory receives the most support. At the same time it is acknowledged that the filling of cracks, fissures, and cavities with mineral

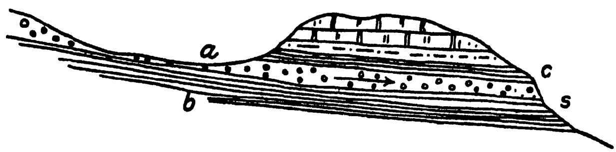


FIG. 248.—Showing natural spring.

(a) Porous stratum.
(b) Lower impervious confining bed.
(c) Upper impervious confining bed.
(s) Natural spring.

matter is usually the work of meteoric waters, as also is the weathering and oxidation of the outcrops of lodes and secondary enrichment.

The processes of lateral secretion by meteoric waters may therefore be regarded as supplementary to the work of the ascending magmatic waters and gases.

WATER SUPPLY.

Water for domestic, manufacturing, and irrigation purposes may be obtained from rivers, lakes, natural springs, and artificial wells. Medicinal waters are usually derived from natural and artificial springs.

Natural Springs.—The requirements of a natural spring (fig. 248) are—

(1) A constant supply of water.
(2) A porous or permeable water-bearing stratum.
(3) Confining beds below and above the water-bearing stratum.
(4) A natural outlet at some point below the inlet or fountain-head.

When rain-water falls on a porous or pervious stratum, it will travel downwards till it reaches an impervious stratum or unfissured rock, along the plane of which it will travel till it reaches the surface, where it will form a natural spring. Obviously such a spring can only be formed where the porous water-bearing stratum crops out at the surface at a lower level than the fountain-head, as in a gorge, sea-cliff, hill-slope, or artificial cutting.

A discussion of what forms a porous stratum and adequate confining beds below and above the porous stratum will be found under the heading *Artesian Wells.*

Artesian Wells.

When underground water existing under hydraulic pressure is tapped by a well or bore-hole, it forms what is called an *artesian well*. The pressure may or may not be sufficient to cause the water to overflow at the surface.

The principle underlying the flow of artesian wells is based on the physical law that imprisoned water always tends to rise to the height of the inlet or fountain-head. In other words, gravity is the main cause of artesian flow.

The main requirements for an artesian flow of water are—

(1) An adequate and constant supply of water.
(2) A porous stratum to act as a reservoir and channel for the underground flow.
(3) A confining stratum below and above the porous stratum or water-bearing bed.
(4) Absence of an outlet for the water at a lower level than the fountain-head.

Porous Stratum.—The ideal water-bearing stratum is a bed of sand, gravel, or porous sandstone; but any rock that is crushed or jointed, or possesses distinct bedding planes, pores, vesicles, cracks, openings, or passages of any kind whatever may form an effective reservoir or source of underground water.

Confining Strata.—The best confining stratum is a bed of clay, marl, or shale; but any compact unfissured rock, or even any constantly saturated semi-porous stratum, may act as an effective confining stratum provided it is *less* porous and offers a *greater* frictional resistance to the flow of water than the water-bearing stratum.

Water will always flow with the greatest freedom through the stratum that offers the least frictional resistance.

Standing water will always rise to its own level independently of friction, but running water cannot do so on account of the loss of *head* or pressure in overcoming the resistance offered to the flow by the interstices of the rock. As the size of the pores or interstices diminish, the frictional resistance increases with extraordinary rapidity, being inversely proportional to the diameter. For example, the frictional resistance to the flow of water in a half-inch tube is four times that of an inch tube of the same length. Herein we discover why a semi-porous stratum with small interstitial pores or openings may be an effective confining stratum for a water-bearing bed.

Arrangement of Strata.—The ideal arrangement of the strata to give the necessary pressure or head for an artesian well is the basin or trough (fig. 249), and next to that the sloping plain (fig. 250).

One, two, or more water-bearing beds may occur in the same basin or sloping plain.

The sloping alluvial plain is common on the coasts of most countries, and nearly always contains water-bearing beds. The alluvium usually consists of alternations of sand, gravel, and clay, with frequently peaty layers. The material is mostly fluviatile, hence the beds vary greatly in thickness and extent. Going seaward the material usually becomes smaller in size; and a bed of gravel may pass into a bed of sand, and a bed of sand into clay or silt.

If the water-bearing beds crop out at the surface, they merely form ordinary surface springs; but when they extend beneath the sea, as so frequently happens with maritime plains, the fresh water rises against the pressure of the sea water, which seals up the open ends of the beds, preventing the escape of the fresh water wherever the *head* of the fresh water is less than that of the sea

water. On account of its greater density, a column of sea water 100 feet high will support a column of fresh water nearly 103 feet high.

If the water-bearing bed is traversed by a fault, igneous dyke, or mineral lode, the downward course of the water may be stopped, and if the wall-rock is pervious, the water will rise upwards till it reaches the surface.

Artesian water may often be obtained in tilted strata, such as slates or schists, where the rain-water follows the bedding or foliation planes.

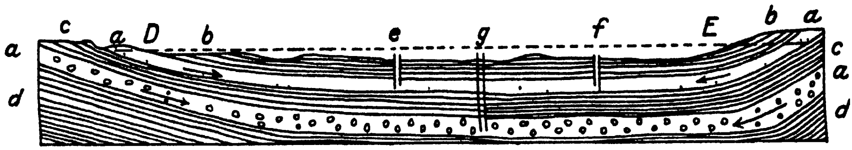


FIG. 249.—Section of artesian basin.

(a–a) Porous strata.
(b, c, and d) Confining beds above and below a–a.
(D E) Height of intake or fountain-head.
(e, f, and g) Flowing wells; e and f from upper water-bearing stratum, g from lower.

Source of Underground Water—The main source of artesian water is the rain-water which percolates into the ground. The supplementary sources of supply are—

(a) The residual water left in sedimentary rocks since the time of their deposition.
(b) Water released by dehydration of rocks and minerals.
(c) Plutonic or juvenile water derived from the interior of the earth.

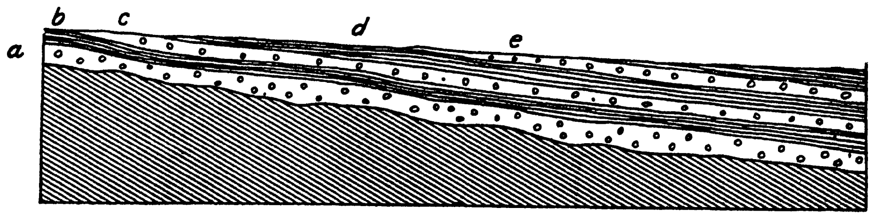


FIG. 250.—Section of artesian sloping plain.

(a) Porous bed resting on bed-rock.
(b and d) Confining beds of finer sand and clay.
(c and e) Porous beds.

Sediments laid down on the floor of the sea and in lakes entangle from 10 to 40 per cent. of their volume of water. Ordinary sands hold about one-third their volume of water. During consolidation and uplift, the greater portion of the water will escape, except where the beds are arranged in a trough or syncline. Most consolidated sedimentary rocks retain from 5 to 10 per cent. of water.

Minerals when first formed are in the hydrated condition, but through the influence of heat and pressure they become dehydrated, particularly during the process of crystallisation or metamorphism. Gelatinous and opaline silica becomes changed to quartz; amorphous limestones to crystalline limestones, mainly composed of calcite; peat and lignite become hard anhydrous coals.

Probably the bulk of the water expelled during dehydration passed upwards

and is absorbed in the unaltered porous strata above, where it may remain under pressure until liberated by artesian wells.

During subsidence resulting from crustal movements, sandstones and other porous rocks charged with meteoric water, or with the water of deposition, may reach a zone where the water is expelled by heat and rock-pressure. The tendency of such expelled water will be to ascend into the higher unaltered beds, where it may accumulate, or it may rise to the surface and escape unobserved, or as natural springs.

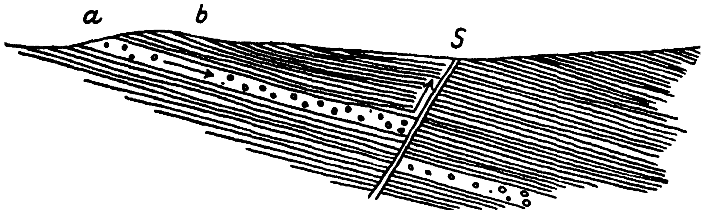


FIG. 251.—Showing fault-spring.
(*a*) Porous stratum. (*b*) Impervious bed. (*s*) Spring.

The main source of the artesian water derived from alluvial drifts is obviously meteoric. The quantity of water derived from deep-seated sources is in this case probably so small as to be negligible.

The artesian water derived from bore-holes in the older formations in arid regions may be partly meteoric and partly uprising deep-seated water.

Nearly all lavas and igneous magmas contain a considerable quantity of water, but whether this water is brought up from the deep interior or merely derived from the rocks with which the uprising magma comes in contact, is unknown. It is quite certain that a cooling magma expels enormous volumes of steam, much of which must be condensed in the cooler zones of sedimentary

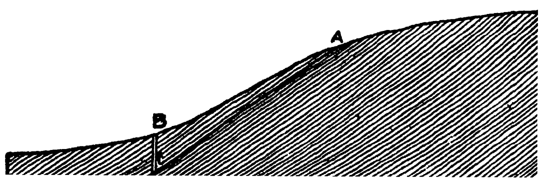


FIG. 252.—Showing flow along bedding planes.
A, Porous strata. B, Artesian wells.

rocks, where, in favourable circumstances, it will accumulate and supplement the supply derived from rainfall.

Factors in Artesian Flow.—The controlling factor in artesian flow is hydraulic pressure or *head*. Among the many modifying causes are—

Constant Factors: (*a*) Size of pores or openings in the water-bearing stratum.
(*b*) Frictional resistance, which is dependent on the size of pores and distance of flow from fountain-head.
(*c*) Rock-temperature, which affects the viscosity and density of the water.
(*d*) Rock-pressure.
(*e*) Conditions of leakage.

Variable Factors: (*a*) Barometric pressure, diurnal and seasonal.
(*b*) Surface temperature affecting the density of water.

Local Artesian Waters.—The best water-bearing rock in England is the oolitic limestone in Lincolnshire, which contains many spouting wells.

The Chalk is water-bearing in places, but irregular and often nearly dry.

The Keuper marl yields good brewing water at Newark, Burton, and Leicester, but the amount is small and variable. The Keuper sandstone gives a good supply of soft water.

The Permian Sandstones and Magnesian Limestone in some places yield a copious supply of good water.

The Lower Greensand sometimes furnishes a considerable flow, and, as a rule, the more abundant the supply, the better the quality. With a small flow the water is often ferruginous.

The Lias clays are liable to produce saline waters, as also is the London Clay.

The Lower Eocene beds in the London Basin, below the London Clay, yield a fair supply which is often slightly alkaline.

An abundant supply of artesian water is obtained in the United States along the Atlantic fringe and Mexican Gulf Plain from the Cretaceous and Tertiary rocks, at depths varying from 50 feet along the inland border to 1000 feet on the coast-line.

In the Great Plains region of the Western Region the Dakota Sandstone is a valuable source of artesian water, which is extensively used for irrigation in the arid regions of South Dakota, Nebraska, and Kansas.

In Western Queensland enormous quantities of artesian water are obtained from the Mesozoic sandstones underlying the Cretaceous Rolling Downs Formation.

Medicinal Springs.—Many mineralised waters possess valuable therapeutic properties. Most medicinal springs occur in volcanic regions; among the best known being those of the Yellowstone National Park and Rotorua, New Zealand.

Medicinal waters according to their composition may be grouped as follows:—

(1) *Alkaline*, containing carbonate of soda and carbonic acid—Vichy, Saratoga; and Puriri, Rotorua, N.Z.

(2) *Bitter*, containing sulphate of magnesia and soda—Sedlitz; Rotorua.

(3) *Muriated*, with mainly common salt—Cheltenham, Wiesbaden, Hanmer, N.Z.

(4) *Calcareous*, with sulphate or carbonate of lime as the main constituent —Bath.

(5) *Sulphurous* or *Hepatic*, with alkaline sulphides and sulphuretted hydrogen, and frequently free sulphuric acid—Harrogate, Aix-la-Chapelle, and Rotorua.

Many mineral waters in Europe, America, and New Zealand have been shown to possess radio-active properties.

The temperature of mineral springs varies from 50° or 60° Fahr. to 212° Fahr. The temperature of the alkaline waters, as their deep-seated origin would suggest, is usually high, ranging from 180° to 212° Fahr.; while that of acid waters, which usually derive their acid constituents from contact with superficial oxidising masses of pyrites, is generally low, as a rule ranging from 90° to 110° Fahr.

But the temperature is dependent on local conditions; hence that of some alkaline waters, like Puriri, is low, while that of some acid waters is abnormally high.

Rock Temperatures in Mining.

During the driving of the St. Gotthard railway tunnel, the temperature of the rock was found to increase at the rate of 1° Fahr. for every 60 feet from the surface, and for some considerable time this rate was regarded as normal for all parts of the earth's crust, and for all depths. These beliefs are now known to be erroneous. Observations taken in deep mines and bore-holes in various parts of the globe have shown—

(*a*) That the temperature-gradient is not the same in all places.

The following temperature-gradients have been recorded :—

Comstock lode	1° Fahr. for every	30	feet in depth.
Thames lodes	1° ,, ,,	45	,, ,,
St. Gotthard tunnel	1° ,, ,,	60	,, ,,
Bendigo mines	1° ,, ,,	75	,, ,,
Tamarack Mine, Lake Superior . .	1° ,, ,,	100	,, ,,
St. John del Rey	1° ,, ,,	126	,, ,,
Rand Gold mines	1° ,, ,,	200	,, ,,
Calumet and Hecla Mine, Lake Superior	1° ,, ,,	223	,, ,,

From the above it will be seen that some parts of the crust are abnormally hot, while others are abnormally cold.

In the Wheeling oil-well, Western Virginia, 4462 feet deep, both when wet and dry, the increase of temperature was 1° Fahr. for every 80 to 90 feet in the upper portion, and 1° Fahr. for every 60 feet in the lower.

Observation taken in bore-holes of Czuchow, near Czerwionka, Silesia, 7280 feet deep; at Paruschovitz (near Rybnik) in the same coal-field, 6510 feet deep; at Schubin in Posen, 6988 feet deep; at Schladenbach, near Leipsic, 5630 feet deep, and other deep bore-holes, have confirmed the view—

(*b*) That the temperature-gradient increases with the depth.

The workings of the St. John del Rey mine, in the State of Minas Gæras, Brazil, have reached a vertical depth of 6326 feet below the surface. At the bottom the temperature is 116° F. when the ground is first broken; and the natural increase of temperature is one degree for 126 feet of depth. This is the deepest mine in the globe.[1]

Peterson's formula for earth-temperature is—

$$t=8{\cdot}29+2{\cdot}154\frac{d}{100},$$

where

t=temperature in degrees C°.
d=depth in metres.

[1] *The Mining and Scientific Press*, vol. cxix., No. 3, 1919, p. 76.

CHAPTER XXXVII.

ELEMENTS OF FIELD GEOLOGY AND GEOLOGICAL SURVEYING.

THE essential requirements of geological surveying is the ability to run natural sections accurately and methodically. And the running of natural sections is an art calling for the open mind, the shrewd, observant eye, sound judgment, a good knowledge of first principles, and a large measure of common sense.

The chief concern of the field geologist is to observe and plot the boundaries, strikes, and dips of all strata, or groups of strata, present in the area under review; to map the position of dykes and other igneous rocks, of faults, lodes, coal-seams, and mineral deposits. His report or thesis deals with the character, thickness, arrangement, age, distribution, and relationships of the stratified formations; with the character, composition, mode of occurrence, tectonic and other effects of intrusive rocks; and with the clays, stones, ores, and minerals of economic importance. Having mastered the geological structure, the geologist may, with some confidence, review the character and genesis of the topographical features.

The best way to learn the methods of exact observation is to attempt the geological survey of some area of simple structure. But before making this attempt it will be necessary to acquire some experience in field observation, and a good way to gain this is to go over some area that has been already mapped and described by an experienced field geologist. Follow the clearest lines of section, carefully note and record the succession and arrangement of the strata, and verify all your observations by comparing them with those recorded on the maps. In many cases you will find that the veteran geologist, aided by a wide experience of geological structures and a knowledge of the succession gained by his investigation of the same formations elsewhere, has been able to read a meaning into isolated facts and occurrences that to you are almost meaningless. Remember that all the facts relating to the geological structure of a district are not always fully disclosed in any one section. Some important point, relating to the geological succession, may be established in one section, and another point in some other section. Do not form conclusions based on obscure or complicated sections. Sections that leave room for two obvious lines of interpretation by two independent observers are frequently the cause of much useless contention, and ought to be avoided when possible. When all the sections in a district are obscure, the interpretation will sometimes be supplied by the clearer sections of a neighbouring or even distant area. When the stratigraphical succession is involved, the problem should be assiduously attacked from the palæontological standpoint.

Before you go to the field take care to get copies of the best geological and topographical maps obtainable of the area you have selected for your preliminary survey. Read all the reports dealing with the structure of the district, and make a summary of the geology for your guidance in the field.

If you possess a fair knowledge of first principles, a good eye for country, and the persistency that overcomes all difficulties, you will soon be able to carry out useful, trustworthy work. Do not expect to unravel all the intricacies of the geology in a day or a week. You will usually find that as the mapping progresses, the geological structure will gradually unfold itself.

Field Equipment.—The equipment for field work should include a 3-inch prismatic compass with metallic card for observing strikes and dips, a 5-inch Abney level for measuring angles of dip, a 3-inch pocket spirit-level, a field-book with a stout cover, a short scale, a 4-inch brass protractor, a 3-inch aneroid barometer, a 66-feet tape, a geological hammer, geological pick, a set of light steel chisels for collecting fossils, and a stout leather bag.

An indispensable part of the equipment is a large-scale topographical map on which the field observations are plotted as the work proceeds. A scale of twenty chains to the inch will be found suitable for ordinary surveys, and a scale of ten chains to the inch for more detailed work.

Make a tracing on paper of the portion of ground to be examined during one or two days, and fix it with paste round the edges in a stiff board portfolio. The observations are marked on the tracing as they are made in the field and afterwards transferred to the topographical map. Each tracing should show the cardinal points of the compass, to enable the strikes and dips to be plotted with the protractor, either in the field or on your return to your headquarters.

The collecting of fossils may be carried on at the same time as the field survey, but, as a rule, it is best to complete the field traverses and thereafter devote your undivided attention to the collecting of fossils. When the mapping and collecting are carried on at the same time there is always a danger that one or both may suffer. Besides, after the district is examined and mapped, you will possess a better knowledge of the fossiliferous beds and of the places where they are likely to prove the most productive. If the examination were of the nature of a rapid reconnaissance, it is the duty of the geologist, while running the traverses, to supplement his field observation with as ample collections of fossils, rocks, and mineral specimens as the time and circumstances will permit.

Rock and mineral specimens are usually collected during the progress of the field traverses, marked with small gummed labels, and then wrapped separately in pieces of paper on which the label number is also marked. The number and locality of the specimen are carefully recorded in the field-book.

A day or even a few days spent in a rapid reconnaissance of the district is usually well spent. By this procedure you will obtain a broad view of the topographical features and general geological structure, which will enable you to arrange your campaign and mode of attack on a systematic basis. Moreover, before you begin the detailed survey you ought to have the lay of the country clearly impressed on your mind.

The field traverses follow all the main streams and their tributaries; also all the salient spurs, ridges, and prominent escarpments.

General Field Procedure.—The general field procedure comprises an examination of all cliffs, rock-outcrops, and escarpments, the position of which should be carefully marked on the field-map.

The points that should be specially recorded in the field-book are a description of the form and extent of the outcrop; character, thickness, strike, and dip of the different strata; height above sea-level or some other known datum; and the topographical features formed by the various rocks.

Make profile and longitudinal diagrams in your field-book of all prominent cliffs, outcrops, and escarpments. The profile is necessary in order to show the

relationship and arrangement of the strata. These sketches need not be drawn to scale, but they should show the direction, height, and length of the portion of the section represented, together with references to the different beds, etc.

The position and extent of the fossiliferous beds should be noted, and a provisional list made of the more abundant fossils.

Take care to record the presence of all igneous masses, dykes, rills, or lava-flows; and indicate their position and boundaries on the map. Search for contacts between the igneous rock and the associated sedimentary rocks, and make a note of the effects due to thermal metamorphism, at the same time collecting rock specimens at short intervals to illustrate the progressive alteration of the clastic rocks. It is also important to select a series of specimens of the igneous rock from the selvedge inwards, in order to be able to ascertain by analysis and laboratory examination what effect, if any, the clastic rock has had on the intruding molten magma.

Faults are features of special interest frequently seen in the face of steep sea-cliffs or walls of deep ravines. Their vertical and horizontal displacement, strike, and dip should be recorded in the field-book, and their course marked on the map. Faults of large displacement show their existence by repetitions of the strata, or by bringing one rock-formation up against another. Such faults are disclosed by the mapping.

The thickness and character of the surface soils may be noted and recorded, but no attempt should be made to show the soils on the map, as this would obscure the distribution of the rock-formations. Special soil-maps are prepared for agricultural purposes.

A careful examination should be made of all accessible mine workings and mine plans, from which much valuable information relating to the geological arrangement of the strata may be frequently gleaned.

The outcrop of coal-seams, mineral deposits, and lodes should be indicated on the map, and a full description of the strike, dip, extent, and general character of the deposit recorded in the field-book. Representative samples of the coal or mineral should be collected for future examination.

Do not allow yourself to be hurried in making your observations. Undue haste may lead to errors in observation and the drawing of crude, ill-considered conclusions. Your interpretation of the geological structure may be altogether wrong and little harm come of it. The all-important point is to be sure of your facts. Always remember that every fact correctly recorded advances the geology of your district one step forward.

Learn to rely on the judgment of older and more experienced observers than yourself, and in your writings do not forget to acknowledge your indebtedness to the work of previous workers in the same field. To utilise the work of others without frank acknowledgment, or to recognise the conclusions of others only when you differ from them, tends to lower the value of your own work.

Do not be too ready to challenge the views of the veteran geologists who have preceded you, and do not try to exalt yourself by holding up their differences. As you gain more experience the more will you respect the opinion of the older geologists.

When you come to construct opinions and draw conclusions, bear in mind that the obvious is not always true. Early writers in New Zealand found broken bones of the gigantic Dinornis at some old native camping-places in Otago, and hastily concluded that the early Maori was a moa-hunter. The association of Maori and moa bones led at once to the conclusion that the two were contemporary. But closer inquiry failed to confirm this view. Moa bones were scattered plentifully over many parts of Otago even at the

advent of the first white settlers fifty years ago, and are still not uncommon in places. At the advent of the Maori, moa bones must have been even more abundant, and who can doubt that a native so highly intelligent and so observant of all natural phenomena would fail to see and collect them. It is significant that the prolific tradition and song of the Maori, rich enough in elaborate detail of the hunting and snaring of the wood-pigeon, kaka, huia, weka, kiwi, tui, and other small birds, should be silent as to the gigantic moa. If the Maori had ever hunted and killed this stately bird, it is certain that his descendants would have preserved the fact in many picturesque traditions.

Accidents may lead to curious associations. The Yakuts of the frozen taiga of Northern Siberia trade in mammoth ivory. Their dogs have even dined off the frozen flesh of this extinct elephant. Perhaps early man did the same in Europe long after the retreat of the Pleistocene ice-sheet. The intimate association of the North Siberian and the mammoth does not prove that they are now or ever were coeval.

The Observation of Strike and Dip.—This is relatively simple where good rock outcrops are exposed at the surface, but certain precautions must be observed to ensure accuracy. The strike is the horizontal line along the bedding-plane of the rock ; and the first precaution is to satisfy yourself that

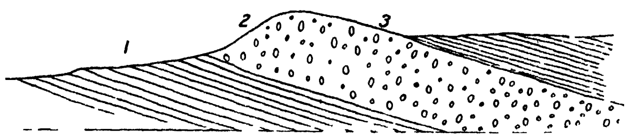


FIG. 253.—Unstratified rock lying between two stratified beds.
1 and 3, Stratified rock. 2, Unstratified rock.

the plane before you is a true bedding-plane and not a joint-plane. In most cases the bedding-plane can be distinguished by some difference in colour, texture, or composition of the material.

The bedding-planes of shales, flaggy sandstones, flaggy limestones, and of all thin-bedded alternating argillites, sandstones, and limestones are easily distinguished. In most cases a clastic rock splits more or less readily in the direction parallel with the original plane of deposition.

The bedding-planes of massive beds of conglomerate are frequently indicated by intercalated layers of sand or clay ; of chalk, by lines of flints or fossils ; of marine clays, by lines of shells, by layers of harder materal, or by lines of hard nodules ; of sandstones, by lines of material of different texture or colour, or by layers of fossils.

Many massive deposits of limestone, claystone, sandstone, and conglomerate exhibit no recognisable bedding-planes. When such a deposit lies between two stratified beds that are parallel to one another, its bedding-plane is usually conformable to that of the enclosing beds (fig. 253).

But it is not safe to assume on the mere evidence of apparent parallelism of the associated strata that the unstratified rock is invariably conformable to the one on which it rests. The two rocks may, after all, belong to different formations, separated by a wide hiatus notwithstanding the apparent physical conformity of the outcrop (fig. 254).

Observing the Strike.—Expose as long a surface of the bedding-plane as possible, and on it, with the aid of the pocket spirit-level, draw a horizontal line with a sharp fragment of stone ; or if there is a long exposure of rock,

mark the horizontal line along the outcrop with small stones or stakes set at intervals. Observe the bearing or course of this line with a pocket-compass, or, better still, and more accurately, with the prismatic compass. Record the bearing, which is the strike required.

Highly inclined beds frequently follow a sinuous course along the strike, and care must be taken to obtain the general strike by taking the mean of a number of observations, or by setting out a long line along the outcrop.

The strike may be recorded as, say, N.E.–S.W., or as 45°–225°, which simply means that when you are looking northward along the outcrop the reading is 45°, and when looking southward 225°. All bearings originate from the north point as zero, and, since the two ends of the magnetic needle are always separated by 180°, it is easy to supply the reverse bearing when the reading has been made in one direction only, which is usually the case when using the prismatic compass. For example, if the compass reading be 30°, the reverse reading will be 210°, and the strike may be recorded as 30°–210°; if the bearing be 165°, the reverse bearing will be 345°, the strike being 165°–345°; or if the reading be 275°, the reverse reading will be 95°, hence the strike will be 95°–275°.

The rule to find the reverse bearing is as follows:—When the observed

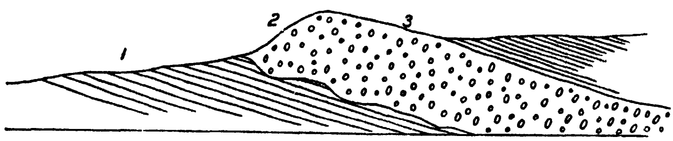


Fig. 254.—Showing unstratified rock unconformable to underlying rock.

1 and 3, Stratified rock. 2, Unstratified rock.

bearing is less than 180°, add 180° to obtain the reverse bearing, and when more than 180°, subtract 180°.

Instead of recording the strike (*i.e.* bearing) as 45°–225°, it may be recorded as 45°, or as 225°, following the practice of professional surveyors and engineers. To record the strike as N.E.–S.W., or 45°–225°, is a redundancy; for, obviously, if the strike or course runs N.E., it must also run S.W., and if 45°, also 225°.

Moreover, when the strike is plotted on the map with the protractor only one direction is used to obtain the course, that is, either 45° or 225°, previously corrected for the magnetic variation.

It will therefore fulfil all requirements and avoid confusion if you simply record the strike as 45°, 62°, 186°, or 347°, as the case may be.

In your amateur field excursions you may use a pocket-compass for observing the strike and dip, but in your more serious work it will be necessary to adopt the field procedure of the experienced geological surveyor.

Be careful to check all your observations and records by repetition. It is never safe to depend on a single observation. Observe the strike and record the reading in your field-book. Again, observe the bearing, note the reading, and compare it with the recorded bearing. By this procedure both the observation and the record are checked.

Take special care to satisfy yourself that the ledge of rock or outcrop where you have made your observation is *in situ* and not a fallen block. In deep gorges and steep sea-cliffs, weak rocks, such as shales, thin bedded clays, and soft sandstones, fissile slates, mica-schists, and phyllite, are frequently distorted where the walls run parallel to or run obliquely across the strike. In such

cases the most trustworthy observations for strike and dip are obtained from the water-worn ledges exposed in the bed of the streams, or on the rocky marine platforms at the foot of the sea-cliffs.

Observing the Dip.—The direction of the dip is always at right angles to the strike, and may incline to the right or left of the strike; that is, if the strike were N.–S. the dip might be towards the east or the west.

The angle of dip is measured with the swinging pointer or bob in the compass-box, or more accurately with the Abney level.

Make your observations for dip and strike at points where the rocks are clearly *in situ*. Avoid large tabular masses detached from the main outcrop. These may have become canted by the partial undermining of an underlying softer stratum by weathering or underground chemical corrosion.

False-bedding will seldom be misleading, except on small exposures.

Be specially careful concerning the direction and amount of dip in the walls of deep gorges and steep cliffs. In such situations the outcrops of the strata are frequently bent and warped by the weight of the superincumbent rocks; and by their own weight where they are unsupported. Outcrop curvature is common in all mountain regions where the rocks are weak (fig. 255). At

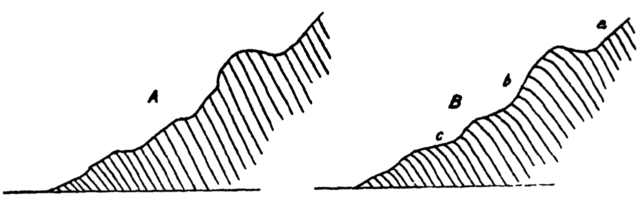


FIG. 255.—Showing effects of outcrop curvature.

A, Before curvature. B, After curvature.

(*a*) Beds not sagging because supported.
(*b*) Beds sagging on steep slope.

places where the outcrop sag is considerable the direction of the dip may be reversed. It is always difficult to obtain trustworthy observations of strike and dip in gorges, ravines, and steep mountain slopes occupied by such weak rocks as phyllite, fissile slates, and shales, especially in recently glaciated regions where the weight of the ice has shattered, bent, and distorted the strata. Failure to recognise the difference between the true dip and the distortion caused by outcrop sag has led to the construction of some wonderful examples of hypothetical folding.

A safe rule is to reject all doubtful observations. Or if recorded in the field-book for future reference, they ought to be marked with a note of interrogation. On no account should they be used as a basis for the interpretation of tectonic structures.

A useful point to remember is that when beds have been tilted at high angles that approach the vertical, a small amount of push in one direction or the other, or an extra amount of pressure, will have caused them to incline to one side or the other. Observe the behaviour of highly inclined strata in the core of a steep anticline. Although you are dealing with a simple anticline, the strata exposed in the core as exposed by denudation along a river course or sea-cliff may be seen to vary from 75° to vertical, then incline in the opposite direction for a short distance, once more become vertical, and again incline a little in one direction or the other (fig. 256). Such rapid variations of inclination are not the result of sharp anticlinal folding, but merely an evidence of

unequal pressure and packing of the strata in the zone of greatest stress. A series of true anticlinal folds in which the limbs approach the vertical position is easily distinguished by the tracing of the repetition of some distinctive stratum.

Measuring the Angle of Dip.—The angle of dip is most accurately measured with the Abney level. The longer the exposed bedding-plane the better. Where possible it is advisable to place a light pine lath 3 feet long along the direction of dip. When the lath is in its proper place the Abney level is laid on it, the

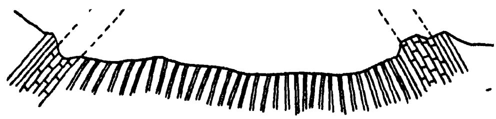


FIG. 256.—Showing variations of dip of highly-inclined strata in the centre of a steep anticline.

arc moved by hand until the bubble is central, and the angle of inclination then read off the scale. By using the lath the minor inequalities of the bedding-plane are avoided.

Observations made in deep mines and in profound mountain gorges, where distinctive beds can be frequently traced by the eye through a vertical height of many thousand feet, have shown that the strata are frequently subject to great variations in the angle and direction of the dip from the surface downwards. In many cases the dip will repeatedly change from one direction to another in a depth of a few thousand feet (fig. 257).

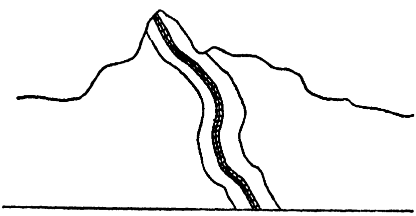


FIG. 257.—Showing changing dip in vertical height.

As a rule, strata that are inclined at high angles at the surface flatten with increasing depth.

Measuring Thickness of Strata.—This is a simple operation, the computation in the case of tilted strata being based on the angle of dip, the angle of the slope of the ground, and the measured distance on the slope.

The different cases that may arise, together with worked-out examples and diagrams, will be found in a little book by the author,[1] and need not be repeated here.

When measuring the thickness of strata take care of repetitions arising from faulting or isoclinal folding. In the case of lacustrine, fluviatile, and estuarine beds, beware of estimating the thickness across the tipping-plane, which is a pseudo bedding-plane (fig. 258). This precaution also applies to all flysch and desert sandstones.

Locating Positions on the Map.—The points at which observations are made in the field must be fixed on the map. If you are provided with a good topo-

[1] James Park, *Text-book of Mining Geology*, 4th edit., chap. iv., Charles Griffin & Co., Limited, London, 1918.

graphical map there will usually be little difficulty in doing this. As a rule the point is fixed by noting its position in relation to some known point. A known point is some spot which you can with certainty locate on the map. It may be a stream, junction, house, corner of some field, fence, or stone wall, angle or bend in the road, quarry reserve, prominent hill or peak, escarpment, trigonometrical station, bay, or headland, etc.

If you take care to start your traverse at some known point, the points of observation will be easily fixed on the map in orderly succession. If your map is deficient in details, it may be necessary for you to measure the distance from point to point with the measuring tape. Prominent outcrops on a distant

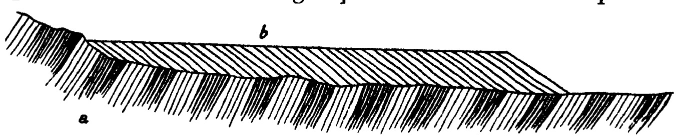


FIG. 258.—Showing pseudo bedding-plane.

(*a*) Bed-rock. (*b*) Deltaic sediments.

range may be easily and accurately fixed by what is called intersections. The procedure is as follows:—Select some prominent outcrop that you can readily distinguish from different points of view. If there is no prominent object, erect a stake with a piece of white or red cotton material tacked to it. Observe the bearing of the object or flag from at least two points which you can with certainty fix on the map. Correct these bearings for magnetic variations so as to reduce them to the true meridian, and carefully plot them with the protractor on your map, using a hard pencil drawn to a fine point. The point of intersection of the two bearings gives the position of the mark or object.

With increasing experience you will acquire considerable skill in locating your field-points on the map.

The strike and dip are shown as in A of the next figure, the axis of anticlines as in B, and the centre of synclines as in C.

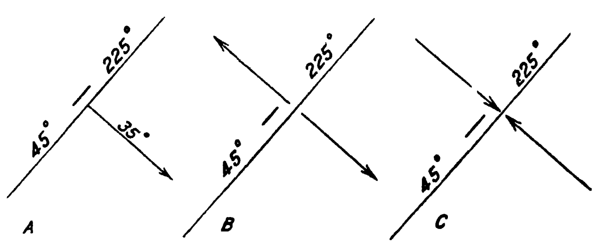


FIG. 259.—Conventional marks for strike and dip.

The bearing of the strike is marked on the line parallel with the strike, and the angle of dip on the line indicating the direction of the dip, as shown in fig. 259, A.

The Geological Map and Sections.—Your first business is to draw up a table of the geological formations present in the area you have examined. Each formation is usually distinguished on the map by a distinctive colour or conventional sign. But a formation may comprise two or more distinct beds or horizons of an outstanding character, each covering a considerable surface area. In such cases it may be expedient to show the subdivisions of one or

more of the formations in different colours; or one colour may be used to distinguish the formation, its subdivisions being shown by various hatching or other conventional signs. The point to aim at is clearness. The attempt to show too much frequently leads to confusion.

The usual practice is first to plot the stream and ridge traverses, then the formation boundaries, and afterwards the subdivisions of the formations.

When the map is finished there only remain the sections to be plotted. Select the lines of section with the view of showing the geological structure, and the relationship of the different formations to one another. The sections are simply profiles of the upper crust, and they ought to be drawn as if you were looking northward.

In systematic surveys the sections are always drawn to natural scale; that is, the horizontal and vertical scales are the same. When the vertical scale is a half, a third, or a fourth of the horizontal, the inclination of the beds is exaggerated and the folds are distorted. Sections drawn on any other than natural scale cannot claim to be much more than diagrammatic.

Use the sea-level datum whenever possible, and let the vertical scale equal the horizontal in all cases except where the surface features are very low and flat.

Select the section-lines, and mark them on the map with a clear pencil line. Mark the ends of the first section A–A, of the second B–B, and so on.

Draw the datum line of the first section, scale off the distance A–A, and at the ends erect perpendiculars. Note that all the work is plotted in pencil before it is coloured and inked in.

Next draw the surface lines, the heights of the various points being obtained from the contour lines on the map or from aneroid or other data. Mark off the boundaries of the formations, as shown along the section-line, on the edge of a strip of paper, and transfer the marks to the section. Draw lines on the section to indicate the boundaries and dips of the formations; apply selected colours for the different formations, ink in the boundaries; and, finally, put on the conventional marks if any are to be used. The fine maps and sections published by Geological Surveys of Great Britain and the United States will be a good guide as to what your map and sections ought to be like.

Preparation of Topographical Maps.—No geological work of any moment, either stratigraphical or petrographical, can be carried out without good topographical maps. Of some regions there are no maps, and sooner or later you will be called on to make your own topographical surveys.

A very useful and fairly accurate topographical survey may be made with the prismatic compass and a 5-chain steel tape, $\frac{1}{8}$ inch wide. A compass traverse is also made of all main and subsidiary streams and roads. The position of houses, fences, and all important natural features are fixed by offsets from the traverse lines when within a distance of two chains, and by intersection bearings when further off.

The stations are marked by stones or small stakes, and numbered in consecutive order; and the usual practice is to post up the day's work at night so as to note the gradual development of the survey and prevent the undue accumulation of field notes.

The angles of elevation, or depression, between the stations are measured with the Abney level; and since all maps are drawn on the horizontal projection, all slope measurements must be reduced to the equivalent horizontal distance for purpose of plotting.

Rule.—The cosine of the angle of elevation (or depression) multiplied by the slope measurement equals the horizontal distance.

The natural or logarithmic cosine may be used in the computation.

The bearings are plotted with a large brass protractor, not less than 6 inches in diameter, to a scale of 10 or 20 chains to the inch, according to the size of the district and the amount of geological detail to be put on it. Whenever it is possible contour lines should be run with the Abney level. The contour intervals will vary with the surface relief from 20 to 200 feet. In low undulating ground the interval may be 20, 30, or more feet, and in mountain regions 100 or 200 feet. The point to be observed in selecting the contour interval is to see that it is not so great as to miss prominent features. If wide intervals were used in low undulating ground many important spurs and hills might

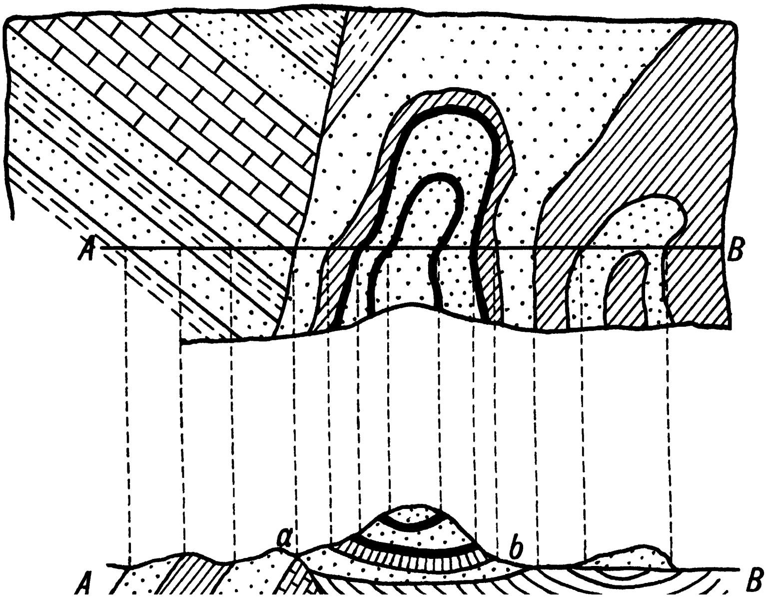


Fig. 259A.—Geological map and section.

(a) Fault plane. (b) Unconformity.

be passed over. Conversely, the selection of too close intervals in a mountainous region might involve the running of an unnecessary amount of lines.

If the geological work you are called upon to undertake is important, your topographical map should be made by theodolite survey with all the traverses oriented on the true meridian. You will find it easier to use a theodolite than a petrographical microscope, and after a little practice you will be able to carry on the work with ease and precision, while the greater accuracy of your work will be a perpetual source of pleasure.

The traverses follow the main streams and ridges, the prismatic compass being used for filling in minor details. The compass bearings are reduced to true bearings by applying the magnetic variation in the manner described in a preceding chapter.

On the excellent topographical maps provided in Europe and many States in America, the magnetic variation is only given at the major trigonometrical stations. As a matter of fact the variation is liable to differ widely in different parts of the same district owing to the proximity of igneous dykes and bosses, some of which may not be exposed at the surface. A serious local deflection

of the needle may be also caused by iron bridges, tram and railway lines, iron houses, iron fences, and other artificial structures in which iron is present in considerable quantity. Hence, you will find it advantageous to determine the variation at many different points during the progress of your theodolite survey. This is quite a simple operation, and may be carried out as follows :—

When the theodolite is set over a station observe the true bearing of some prominent distant object, such as a tree top, church spire, or sharp peak. Record the bearing and the number of the station.

Now unclamp the vernier plate and set it at zero. Then loosen the long box-needle, and swing the instrument round until the needle settles in the N.-S. line. Clamp the bottom plate, and with the bottom tangent-screw orient the instrument exactly in the magnetic meridian. This is effected by bringing the engraved line at the end of the compass-box exactly opposite the north end of the needle.

Now unclamp the vernier plate, direct the telescope to the object previously viewed, and read the bearing. Repeat the operation, and take the mean of the two readings. The difference between this mean magnitude bearing and the true bearing is the magnetic variation at the station of observation, disregarding the small correction for convergence of meridian.

The true meridian is determined at the initial station of the theodolite survey, in the Northern Hemisphere by observations to Polaris, and in the Southern Hemisphere to *a Crucis*, *a Centauri*, or other conspicuous circumpolar star. You will have no difficulty in determining the meridian within half a minute of arc. Detailed instructions as to the methods and procedure to be pursued, together with worked-out examples and diagrams, will be found in a work by the author [1] in which also the methods of contouring with the Abney level are fully described.

To Convert Magnetic Bearings to True Bearings.

All geological and topographical maps are projected on the so-called true meridian ; hence, when the strike of strata is determined with a magnetic compass, it becomes necessary to convert the observed magnetic bearing into a true bearing before it can be plotted on the map.

Conversely, if the strike of a seam or stratum is taken off the map with the view of setting off the course on the ground with a compass, the true bearing must first be converted into a magnetic bearing.

Only in a few places does the true meridian coincide with the magnetic meridian. In most regions the magnetic meridian lies to the east or west of the true meridian. The difference between the two meridians is called the *magnetic variation*, and its amount is usually marked on all topographical and trigonometrical district maps.

In Britain the magnetic meridian is west of the true meridian, and in New Zealand east.

The strike is best determined with a pocket or prismatic compass graduated into 360°, where 360° is north or zero. Obviously, east will be 90°, south=180°, and west=270°.

The advantage of a compass graduated in this way is that all the bearings (*i.e.* courses or strikes) are measured from the north point.

To Convert a Magnetic Bearing to a True Bearing.—Only two cases are likely to occur—namely, the variation will be east or west.

[1] James Park, *Text-book of Theodolite Surveying*, 5th edit., Charles Griffin & Co., Limited. London, 1922.

When the Variation is East.—Rule—To the observed magnetic bearing *add* the variation, and the result will be a true bearing.

In fig. 260 the variation is 15° east of the true meridian, and the compass bearing of line *a b* along the course of a stratum, 100° 50′; find the true meridian. Obviously—

$$100° \ 50' + 15° = 115° \ 50' = \text{true bearing};$$

that is, the corrected bearing in terms of the true meridian is 115° 50′.

When the Variation is West.—Rule—From the observed magnetic bearing *subtract* the variation, and the result will be the true bearing.

In fig. 261 the variation is 12° west of the true meridian, and the compass

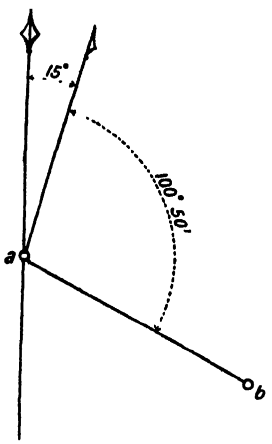


FIG. 260.—Conversion of magnetic bearings to true.

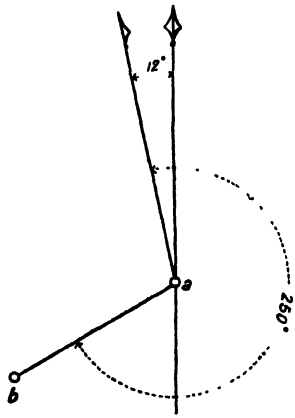


FIG. 261.—Conversion of magnetic bearings to true.

course of a lode is 250°; find the bearing or strike in terms of the true meridian. Here—

$$250° - 12° = 238° = \text{true bearing}.$$

To Convert a True Bearing to a Magnetic Bearing.—This is the converse of the above. When the variation is easterly, *subtract* the variation from the true bearing; and when westerly, *add* it to obtain the corresponding magnetic bearing.

Determination of Strike and Dip from Contoured Map.

The exactitude to be obtained by this method depends on the accuracy of the survey and mapping. The results are trustworthy only when the contours have been run with the spirit-level; the outcrops and contours accurately fixed by theodolite traverse; and the positions plotted by rectangular co-ordinates on a large scale.

To Determine the Strike.—Two outcrops on the same level must be known.

Let A and B be two outcrops of a bed or vein at the same level. Join points A and B with a straight line.

Then the line A B is the direction of the strike, and angle *x* the bearing of the strike in terms of the meridian N.–S., which may be the true meridian or the magnetic meridian, according to the orientation of the map.

At all other levels the strike will be parallel to A B. Thus at point C, which is 100 feet below B, the strike is C E.

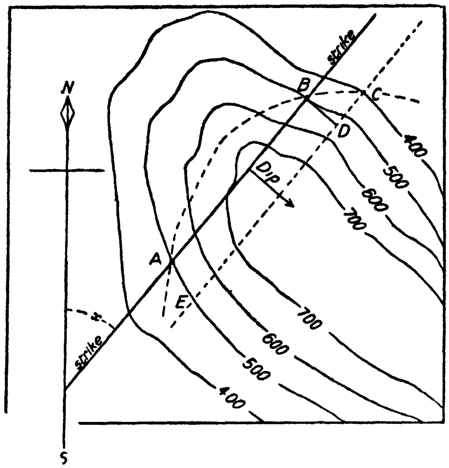


FIG. 262.—Showing graphic determination of strike from contoured map. A, B, C, Outcrop of bed.

To Determine the Dip.—The dip, or more correctly the direction of the dip, is always at right angles to the strike. If we assume that the bearing of the strike is 40° (that is, angle $x=40°$), then the dip being south-easterly, the direction of the dip is $40°+90°=130°$.

If the dip were in the opposite direction, the strike being the same, then its bearing or direction would be—

$$360°+40°=400°$$
$$\text{and } 400°-90°=310°.$$

To Determine the Angle of Dip.—Three points or outcrops must be known, namely, two at the same level and one at a lower or higher level.

(1) Let A, B, and C, fig. 262, be the known outcrops, A and B being at the same level, and C at a lower level, 100 feet below B.
(2) Determine the strike as in the first problem.
(3) Through C draw C E parallel to A B.
(4) At B draw a line B D at right angles to A B, terminating at line C E.
(5) Scale as accurately as you can the length of B D.

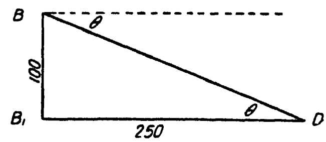


FIG. 263.—Showing profile along B D.

Let B_1 be a point at the same level as C or D, immediately below B, and let $B_1D=250$ feet.

In the right-angled triangle B B_1 D we have given the two sides about the right angle to find the angle of dip, namely, $B_1D=250$ feet, and B $B_1=100$ feet.

Let θ=the angle of dip.

Then—

$$\text{Cot } \theta=\frac{B_1D}{B_1B}, \text{ or } \tan \theta=\frac{B_1B}{B_1D}.$$

By natural tangents—

$$\text{Tan } \theta=\frac{100}{250}=\cdot 4000000=21° \; 48'=\text{angle of dip.}$$

By logarithms—

$$\text{Log } 100 = 2\cdot 0000000$$
$$\text{Log } 250 = 2\cdot 3979400$$
$$\text{Log tan } 21° \; 48' = 9\cdot 6020600$$

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